Doctoral Thesis
Departament d'Enginyeria Telemàtica
(Dept. Network Engineering)

Contributions to the Algorithms and Methodologies for Virtual Infrastructure Provisioning

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a tots els que m'han ajudat, d'alguna manera
o de cap altra, a ésser qui (i el qué) sóc;
i a tu Marina, per aparéixer, per quedar-te, i portar amb tu la il·lusió

Una gota de terra acarícia la mar,
ella és aquella que tant he somiat.
Perquè ella és l'illa, no és un amor normal,
ella és una il·lusió que té gust a sal.
I dins l'olivera el temps s'ha aturat,
un timbal de pedra, boscos i animals.
No som un poeta, jo som escribà,
un illot des d'on escric el que vull cantar demà
Quan m'he allunyat de tu fugint de jo mateix,
dins el pit sentia un dolor que no es veu.
Com una llum en la foscor del meu record,
un camí de claror i pau que ho ompli tot de passió.
És sa meua pressó, sa meua llibertat,
on totes les fronteres són cel, arena i mar.
Tan gros aquest petit món meu,
té un riu per a creuar els seus ponts.
I jo que som natiu, aquí sa meua vida hi viu fent niu
- Illa (BEN CLARK), Versió musicada de Projecte Mut

ABSTRACT

Virtualization is defined as the process consisting of building a virtual resource on top of one or several physical resources, depending on the selected paradigm: aggregation or partitioning. From the networking perspective, over the recent years virtualization became a hot topic in networking research, although the term is not new, neither for networking nor for Information Technology (IT). In virtualization environments, the most significant challenge to be addressed is the virtual infrastructure allocation or embedding one. The problem appears over any networking technology, from wired to wireless domains, including converged physical infrastructures as well as coupled IT and networking infrastructures. This problem has re-gained importance in the last years due to the emergence of novel software-based abstractions, which provide fully-operational interfaces on top of those virtual resources, enabling the emergence of novel business models.

The election of the physical resources upon which the virtual infrastructure will be instantiated becomes fundamental for the virtual infrastructure operation in those virtualized environments, i.e. the election of the physical resources over which the virtual ones will be allocated. In fact, the virtual infrastructure allocation system might be seen as a policy-based system, where, based on the physical infrastructure available, and the set of requests, it will create different virtual infrastructures as a function of the policy, which will indicate the metric to optimize when creating those Virtual Infrastructures (VIs). For example, the infrastructure provider, who is responsible for leasing those virtual infrastructures, may want to optimize the economical cost of the different instantiated virtual slices, or even the overall energy consumption of the slices.

The problem acquires different dimensions when considering heterogeneous resources (e.g. optical network resources and wireless resources) in order to create cross-domain virtual infrastructures; or when it includes IT resources connected at the edges of the different network domains. The first part of the thesis provides an insight on the problem, and different contributions on the algorithms utilized in order to solve the problem. It considers different optical substrate technologies, wireless and wired resources, and it tries to optimize either the total number of virtual infrastructures to be created or either the energy consumed by the resources.

Furthermore, the work proposed in the second part of the dissertation includes a dynamic re-planning approach, which is responsible of dynamically updating already provisioned virtual infrastructures

in order to adapt them to the Cloud-based services. Those services are unpredictable; basically, information regarding the volume and type of service requests is not precisely available in advance of the requests to the VI providers. Cloud services can scale up and down on demand. Therefore, that dynamic adaptation of the infrastructure to the elasticity of the Cloud services requires constant changes. Dynamic re-planning becomes fundamental for virtual infrastructures supporting cloud-based services.

Virtualization can be indistinctly applied to IT servers, network resources, and even network functions. The last part of the work defines the additional scheduling problem, specific for Network Function Virtualization (NFV), which is complementary to the allocation or embedding. NFV aims at decoupling the network functions from the actual hardware where they are executed. Thus, most of the network functions will run on standard virtualized servers by means of software, which is expected to significantly reduce capital expenditures, while at the same time the software automation reduces operational expenditures. The solution for the scheduling aims at minimizing the total execution time for chains of network services running over IT infrastructures.

AGRAÏMENTS

Sens dubte, tot i que aquest fragment que llegiu ara mateix es troba al principi de tot, ha set la última part en ésser escrita. I així ha set perquè fins a l'últim segon podria trobar persones (i objectes!) a qui agrair el viatge que representa la tesi doctoral, materialitzat en aquest document; i més en les meves especials circumstàncies, que han allargat el procés un poc més allà del que és comú.

Esdevé gairebé obvi que l'ordre de les persones (i objectes!) mencionats aquí no guarda cap relació amb el nivell d'importància. Ni el primer té més valor que l'últim, ni l'últim té més valor que el primer.

Només puc demanar perdó a la gent que al llegir aquest fragment no s'hi vegi reflexat implícita o explícitament; en el meu cor i sobretot en el meu cap (qüestions de tamany) sempre hi haurà espai per a tothom.

Al Xavier, per entendre que aquesta col·laboració que vàrem començar fa molts d'anys, abans fins i tot d'un projecte fi de carrera, podia i havia de funcionar a una velocitat diferent; per deixar-me l'espai necessari per a poder compaginar-ho tot, al mateix temps que no ha deixat de guiar-me en la distància, prement la tecla necessària en els moments precisos per no arribar mai tard al tren.

Als meus pares, per moltes coses que podria dir i no acabaríem mai, però per entendre que no sempre el camí més recte és el que porta a millors resultats; per deixar-me fer les corbes del camí al meu estil, i sobretot per donar suport a qualsevol elecció i decisió presa en el camí, independentment dels riscos i resultats. Al meu germà també; per tot el mateix, i per molt més que et dóna un germà gran. I a la Susanna, per fer que sigui feliç. I per suposat a nen Lluc, perquè ens fa més feliços a tots. I també als que han de venir.

A tots els amics i la gent d'Eivissa, que en són tants, i que estan tan distribuïts pel món, que costaria de mencionar-los a tots un a un. Rull, Víctor, Manu, Dani, Pau, Juanan, Dominguez, etc. (i a tots els que em deixo us demano disculpes, però no volia escriure més de mil pàgines) per tots els anys que hem passat, i encara que no enteneu ben bé el que feia, sempre heu entès que era suficient per pagar una cervesa. Aquí el meu petit homenatge després de tants d'anys junts. I també a la gent de la universitat, per totes les hores que varem passar al bar, i també a les classes i a les pràctiques, que en varen ésser menys. Jandro, Darío, Mazas, Muro, el Guiu, José, Álvaro i companyia: arribar fins aquí també té part vostra.

Agrair també a la gent del bàsquet, el "Bosco" (Dusti, Alex, Tomas, Rafa, Triqui, José, Nacho, Xixo, Bal, Xuxu, Torres, Rock, Toti i tots els que van passant) per fer de cada dimecres una festa on, a més d'ilustrar-nos a hòsties, gaudim d'un fantàstic sopar on poder passar per dalt de les rutines diàries.

No puc deixar d'esmentar als *gaylords*, perquè ells, entre d'altres coses, saben que un Philosophiæ Doctor (PhD), en contra del que es pensa normalment, neix, i no es fa. Jetler, Sergi, Pau, Hellkike, Pinyaki, Raul, Marc i Alex, amb qui a més de compartir hores de bici, i sortides de córrer, tenim meravelloses tertúlies virtuals sobre qualsevol - i quan dic qualsevol, vull dir qualsevol tema que pugui ocórrer a dins de l'univers conegut. Llàstima que els resultats de la virtualització no siguin mesurables en watts.

No pot faltar tota la gent d'i2CAT. Al Sergi, i l'Eduard, per ésser els primers en confiar en mi, quan encara no sabia gairebé ni programar. Al Joan Antoni per ensenyar-me a ésser crític no només en el fons, sinó també en la forma. I a l'Edu ara, per deixar-me llibertat per fer tota la feina. Al Josep, Leo, Carlos, Marc, Pau, Adrian, Isart, Julio, Jofre, Celia, Ester, Barrera, Fernández, Benseny, Castro, i tots els companys que m'oblido i amb qui hem passat tantes hores, viatges i hem vist com i2CAT assolia un objectiu darrera l'altre. També a tota la gent de gestió que ens fa les tasques diàries més fàcils i a tota la gent de direcció. Al Felipe, que tot i no ésser d'i2CAT va estar en els moments inicials del viatge. He après molt durant tots aquests anys a la fundació. Els esforços valen la pena.

A tota la gent de tots els grups de *whatsapp* que tinc, que no són pocs, per fer que el meu temps sigui més entretingut, tot i que us tingui silenciats. A tota la gent amb qui he treballat al llarg de la vida, que en són molts i de molts països. A tota la gent amb qui m'he creuat i d'alguna manera m'ha ajudat a assolir aquest objectiu. A la família política, Hèctor, Imma, Marga, Biel, per tractar-me con un més dels vostres, us asseguro que també heu ajudat. A la gent de Madrid i tot els festivals que hem fet, vertader és l'amor de festival. I, en general, a tots els que no he mencionat explícitament, això també té una part vostra: gràcies.

Per últim, i (ara sí, és l'hora) més important, a la Marina, per aguantar-me en el dia a dia; per entendre els sacrificis que he fet de moltes nits i moltes estones lliures. Per entendre els meus esforços. Per ajudar-me i per enamorar-me. I per saber esperar. Com que no puc agrair-te tot el que voldria en unes línies, ho faré en una vida, que esperem tingui més espai que no pas aquí.

El poc que resta és demanar perdó a tots i totes els que m'hagi deixat de citar aquí; no us preocupeu, també us ho agraeixo. Gràcies a totes i tots, ha estat un procés o viatge meravellós

PREFACE

*"It is not at all uncommon for doctoral researchers to think about the PhD as a journey. And they generally use the PhD-as-journey as more than a simple metaphor – it becomes a, even **the** way of explaining to other people what has and is going on in their candidature. The PhD-as-journey becomes a way of telling self and others the story of the PhD process and the various experiences, emotions, and challenges along the way. The notion of the journey sums up the sense of movement, personal growth and change. The journey becomes a meaningful way of narrating the ups and downs of the whole doctoral experience"* [Tho15].

But how good a metaphor is it really? As Christina Hughes and Malcolm Tight [HT13] have pointed out, the journey is a pretty vague concept. There are several kinds of possible journeys, apart from life itself, some pleasant some not, some risky some not, some under uncertainty, some well planned and controlled. There is at least a distinct journey per human being. Concerning what a PhD journey is, again Hughes and Tight [HT13] suggest that the most common PhD journey narrative is actually a quest, a search for a treasure, promised land and/or wisdom[a]. For example, as Thomson mentions, *"think Holy Grail here, Jason and Argonauts and the Golden Fleece... Well, not exactly. It is arguable that the doctorate journey is most often a Pilgrim's Progress, with staged posts of hope, loss, fear, doubt, and achievement"*[b]. This Pilgrim's Progress is in some ways an apt allegory for the doctorate as it captures the loneliness, confusion, loss of voice and avoidance of temptations in the process, as well as the final arrival at the heavenly destination.

a El somiat viatge a Ítaca seria l'analogia més propera a la nostra cultura. "Viatge a Ítaca" és un poema de Konstantinos Kavafis (1863-1933), escrit el 1911, basat en l'Odissea d'Homer. Anys després Carles Riba el va traduir al català, i més tard Lluís Llach el va musicar i popularitzar amb una cançó al seu disc titulat també "Viatge a Itaca" (1975). El viatge marítim a Ítaca és una al·legoria clàssica de la vida, en el qual el camí, difícil i ple d'aventures, és la vida i el port on s'arribarà finalment és la mort. També es pot entendre com el llarg camí cap a un destí desitjat i llunyà, com per exemple un món millor, i per això és un poema (i una cançó) amb clares connotacions utòpiques. Siga com siga, el que ens ensenya és que en una situació o aventura és **més important el camí que cal recórrer que el propi final** [iG13].

b The Pilgrim's Progress from this world to that which is to come; delivered under the similitude of a Dream is a Christian allegory written by John Bunyan (1628 - 1688), published in 1678. It is regarded as one of the most significant works of religious English literature [aI57, Bun10]. The allegory centres the narration in the journey of Christian, an everyman character, from his hometown, the "City of destruction" - i.e. this world; to the "Celestial City" - i.e. that which is to come: Heaven) atop mount Zion. More information can be found in `http://en.wikipedia.org/wiki/The_Pilgrim's_Progress`

Basically, the doctorate, seen as a journey, is *"a form of work that has involved graft, skills, time, training, and painstaking attention to a specific subject of study over a significant period of time. In such a way it is akin to craft, where the intellectual value of the thesis is the primary consideration"* [HT13].

And as every journey, any PhD has a destination. The manuscript you are about to read summarizes the Pilgrim's progress I have been through during the last years. It is difficult to capture all the achievements in a single document, and it becomes nearly impossible to write down all the small steps walked during the process. However, the manuscript is structured following the logical steps of such journey, which eases both the reading and the writing process.

The reader will find three well differentiated parts within the document. The first part indicates the start of the journey; and as any starting point, it mainly comprehends a surrounding analysis and navigation through different concepts which appear during the journey. It provides a complete context and perspective to the problem (or problems) challenged during the dissertation. At the same time, the analysis includes the study of the state-of-the-art for the relevant topics, aiming to provide a complete context to the specific subject of study (in my case, network virtualization). The work we do during the doctorate journey depends also on the work by others, and it is fundamental we achieve a global knowledge of the topic, before starting the research itself. Think here in the way you plan a holiday travel: you start analyzing the places to go around an area, what to visit, what others are visiting, why are they going there, and hundreds of open questions that need to be solved before starting the journey.

This first part is the door towards the second major part of the activities, where initial contributions on the studied subject are made in conjunction of other people. Basically, in the second part it becomes crucial that you learn how to research, and how to work in order to contribute to the advance of such studied topic. This part comprehends different contributions around the topic, which will pave the way towards the final goal of the dissertation, i.e. propose new solutions or original work within the research community to the specific subject of interest and study. Following with the travel analogy, this part would represent when you get initially got the destination, all the plans and goals, and start the travel.

Finally, the last part comprehends the final goal of any doctoral thesis. It contains the proposals made to the community around the studied topic. Original solutions to the problem, or to specific branches of the problem which have not been proposed and which provide determined benefits with respect to other existing solutions (if any). This is the most important part, although it is always the last one, and the more difficult to achieve.

The three parts are not independent at all, and one part could not exist without the other. The parts are interdependent, and they should be seen as a whole, which at the end comprehends the doctorate journey.

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ACRONYMS

ap Access Point

api Application Programming Interface

argon Advance Reservations in Grid-enabled Optical Networks

atis Alliance for Telecommunications Industry Solutions

atm Asynchronous Transfer Mode

bp Blocking Probability

bss Business Support Systems

bst Base Station

bv-wxc Bandwidth Variable Wavelength Cross Connects

byod Bring Your Own Device

capex Capital Expenditures

cci Call Controller Interface

ccn Content-Centric Networking

cdma Code Division Multiple Access

content Convergence of Wireless Optical Network Resources in support of Cloud services

cots Commercial Off-The-Shelf

cpu Central Processing Unit

dana Distributed Applications and Networks Area

db Storage

dc Data Centre

diffserv Differentiated Service

dip Data Centre Infrastructure Provider

dpi Deep Packet Inspection

drac Dynamic Resource Allocation

dragon Dynamic Resource Allocation via GMPLS Optical Networks

dwdm Dense Wavelength Division Multiplexing

edfa Erbium Doped Fiber Amplifier

eis Enterprise Information System

eis-c Enterprise Information System Consumer

etsi European Telecommunication Standardization Institute

fdma Frequency Division Multiple Access

fh Frequency Hopping

fia Future Internet Assembly

fn Future Network

fpga Field-Programmable Gate Array

fs Frequency Slot

gbr Guaranteed Bit Rate

geysers Generalised Architecture for Dynamic Infrastructure Services

gmpls Generalised Multi-Protocol Label Switching

gmpls+ Generalised Multi-Protocol Label Switching +

g^{2}mpls Grid-enabled Generalised Multi-Protocol Label Switching

gnu Genuinely Not Unix

god Game on Demand

gsm Global System for Mobile communications

hpc High Performance Computing

iaas Infrastructure as a Service

ict Information and Communications Technologies

ietf Internet Engineering Task Force

ilp Integer Linear Programming

intserv Integrated Services

inwg International Network Working Group

ip Internet Protocol

ipc Inter-Process Communication

ipsec Internet Protocol Security

irtf Internet Research Task Force

isp Internet Service Provider

it Information Technology

itc Information Technology and Communication

itu International Telecommunication Union

ivm Infrastructure Virtualization Manager

lb Load Balancer

licl Logical Infrastructure Composition Layer

licl-imf Logical Infrastructure Composition Layer - Information Modelling Framework

lobs Labeled Optical Burst Switching

lobs-h Labeled OBS with Home circuits

lp Linear Programming

lte Long Term Evolution

lte-a Long Term Evolution - Advanced

mac Multiple Access Computer

mems Micro-Electrical Mechanical System

mcc Mobile Cloud Computing

mimo Multiple Input Multiple Output

mips Million Instructions Per Second

mpls Multi-Protocol Label Switching

mvno Mobile Virtual Network Operator

nar Non-linear Autoregressive Analysis

ncc Network Call Controller

ncp Network Control Plane

ncp+ Enhanced(+) Network Control Plane

nf Network Function

nf-fg Network Function Forwarding Graph

nfv Network Function Virtualization

nfvi Network Function Virtualization Infrastructure

nfvi-pop NFV Infrastructure - Point of Pressence

nfvo Network Functions Virtualization Orchestrator

nfvrg Network Function Virtualization Research Group

ngn Next Generation Network

nist National Institute of Standards and Technology

nlp Non-linear Programming

np Non-deterministic Polynomial

ns Network Service

nsp Network Service Plane

nve Network Virtualization Environment

nvp Network Virtualization Platform

nvs Network Virtualization Substrate

obs Optical Burst Switching

occi Open Cloud Computing Interface

oeo Optical - Electrical - Optical

ofdm Orthogonal Frequency Division Multiplexing

ofdma Orthogonal Frequency Division Multiple Access

ogf Open Grid Forum

oip Optical Infrastructure Provider

onf Open Networking Foundation

oofdm Optical Orthogonal Frequency Division Multiplexing

oofdma Optical Orthogonal Frequency Division Multiple Access

opex Operational Expenditures

ops Optical Packet Switching

opst Optical Packet Switch and Transport

os Operating System

osgi Open Service Gateway initiative

OSI Open Systems Interconnection

OSS Operational Support Systems

OTN Optical Transport Network

OXC Optical Cross Connect

PCE Path Computation Element

PHD Philosophiæ Doctor

PHOSPHORUS Lambda User Controlled Infrastructure for European Research

PI Physical Infrastructure

PIC Photonic Integrated Circuits

PIP Physical Infrastructure Provider

PLI Physical Layer Impairment

PON Passive Optical Network

PR Physical Resource

QOE Quality of Experience

QOS Quality of Service

RAN Radio Access Network

RAND Research and Development

REST Representational State Transfer

ROADM Reconfigurable Optical Add-Drop Multiplexer

RORA Resource-Ownership Role-Actor

RSA Routing and Spectrum Allocation

RWA Routing and Wavelength Assignment

SAN Storage Area Network

SDF Service Delivery Framework

SDH Synchronous Digital Hierarchy

SDMA Space Division Multiple Access

SDN Software-Defined Networking

SDU Service Data Unit

SFC Service Function Chain

SFC-WG Service Function Chaining Working Group

SFP Small Form-factor Pluggable

SFP+ Small Form-factor Pluggable +

SIP Session Initiation Protocol

SMF Single-mode Fibre

SML Service Middleware Layer

SN Substrate Network

SNMP Simple Network Management Protocol

SLA Service Legal Agreement

SLICE Spectrum-slice Elastic Optical Path Network

SOA Service Oriented Architecture

SP Service Provider

SSID Service Set Identifier

T-NOVA Virtual Network Functions-as-a-Service over Virtualized Infrastructures

TCP Transfer Control Protocol

TDM Time Division Multiplexing

TDMA Time Division Multiple Access

TNM Transport Network Manager

TSON Time-driven Switched Optical Network

UCLP User Controlled Lightpath Provisioning

UNI User-to-Network Interface

USB Universal Service Bus

USRP Universal Software Radio Peripheral

VI Virtual Infrastructure

VIE Virtual Infrastructure Embedding

VIM Virtual Infrastructure Mapping

VIO Virtual Infrastructure Operator

vip Virtual Infrastructure Provider

vir Virtual Infrastructure Request

vm Virtual Machine

vlim Virtual Link Mapping

vn Virtual Node

vne Virtual Network Embedding

vnf Virtual Network Function

vnf-fg Virtual Network Function Forwarding Graph

vnfm Virtual Network Function Manager

vnm Virtual Network Mapping

vnom Virtual Node Mapping

vod Video on Demand

voip Voice over IP

von Virtual Optical Network

vona Virtual Optical Network Allocation

vpn Virtual Private Network

vr Virtual Resource

wan Wide Area Network

wdm Wavelength Division Mulitplexing

wi Worker Instance

wip Wireless Infrastructure Provider

wimax Worldwide Interoperability for Microwave Access

wson Wavelength Switched Optical Networks

wss Wavelength Selective Switch

Part I

ENVIRONMENT

- "Let him your servant be born again from the sea, as you were. Bless him with salt, bless him with stone, bless him with steel."
- "What is dead may never die."
- "What is dead may never die, but rises again, harder and stronger."
AEERON DAMPHAIR (A Song of Ice and Fire)

1 INTRODUCTION

It matters not how strait the gate,
How charged with punishments the scroll,
I am the master of my fate,
I am the captain of my soul..
- WILLIAM ERNEST HENLEY (Invictus)

First impressions are so important. How many times have you heard that? It is true that the first impression —whether it is a first meeting with a person or the first sentence of a paper— sets the stage for a lasting opinion. The introductory paragraph of any paper, long or short, should start with a sentence that piques the interest of your readers [Fle12]. This is not new. In the ancient years, Plato published *The Republica*, where he stated "*The beginning is the most important part of the work*" [Pla11].

First impressions are so important. The beginning is the most important part of the work

Intentionally, the dissertation starts with such an introductory chapter, which aims at piquing the interest of the reader for the rest of the manuscript. The opening chapter comprehends a surrounding navigation through and over the distinct concepts, which the ecosystem of the work is composed of. Several concepts such as optical networks, cloud computing, virtualization, network convergence, Software-Defined Networking (SDN), or even NFV are presented and linked along the first chapter. The challenge faced within this introduction is to provide to the reader sufficient background material and knowledge in order to completely understand the scope, and the environment of the dissertation work.

The introduction represents a complete journey into the different topics, terminology, and major concepts that will be later on utilized as the driving line for the whole dissertation. This will help the reader to understand what happened in the research and innovation community for the last years, as well as to understand the global context of the dissertation.

1.1 OPTICAL NETWORKS, AND CLOUD COMPUTING

After experiencing remarkable rapid growth during the end of the 90s decade, the telecom industry, and optical networking in particular, has been experiencing some challenging times over the past several years [Muk06]. Nevertheless, even though the telecom business market is unsettled today, we need to be ready with the appropriate technologies and engineering solutions to meet the growing bandwidth needs of our information society. Optical networking using Wavelength Division Mulitplexing (WDM) is the technology of choice for meeting these growing demands [Muk97]. Some authors such as Papadimitriou et al. consider in [PPP07] WDM technique as the most important breakthrough in the different approaches in order to increase the capacity of a network that utilizes optical fiber.

When plugging an electric appliance into an outlet, we care neither how how electric power is generated nor how it gets to that outlet. This is possible because electricity is virtualized.

WDM allows many signals to travel concurrently on a single fiber using different wavelengths. This shifted the focus from increasing the data rate at which signals travel inside an optical fiber to increasing the number of channels available simultaneously at potentially lower data rates. Constant advances in this area have unlocked a significant portion of the bandwidth that optical fibers offer [PPP07]. Research and development on optical WDM networks have matured considerably over the past decade. They are being or even have been deployed by telecom network operators all over the world.

Simultaneously to this optical networking paradigm evolution, several technologies such as *cluster*, *grid*, and nowadays, *cloud computing* have remarkably emerged as new computing provisioning paradigms [Buy09]. When plugging an electric appliance into an outlet, we care neither how electric power is generated nor how it gets to that outlet. This is possible because electricity is virtualized; that is, it is already available from a wall socket that hides power generation stations and a huge distribution grid. When extended to information technologies, this concept means delivering useful functions while hiding how their internal works. Computing itself, to be considered fully virtualized, must allow computers to be built from distributed computers such as processing, storage, data, and software resources [Fos03].

Aforementioned technologies have all aimed at allowing access to large amounts of computing power in a fully virtualized manner, by aggregating resources and offering a single system view. In addition, an important aim of these technologies has been delivering computing as a utility. Such utility computing describes a business model for on-demand delivery of computing power [BBG11]. In fact, cloud computing has been coined as an umbrella term to describe a category of sophisticated on-demand computing services initially offered by commercial providers, such as Amazon[a], Google[b], and Microsoft[c]. It denotes a model on which a computing infrastructure is viewed as a *cloud*, from which businesses and individuals access applications from anywhere in the world on demand [BYV+09]. The main princi-

a http://www.amazon.com
b http://www.google.com
c http://www.microsoft.com

ple behind this model is offering computing, storage, and software *as a service*.

The question at this point may be: *Where is the link between optical networks (specially optical networks regarding the huge bandwidth requirements) and clouds?* or even *Why do we present optical networks and cloud computing under the same section?*. They may seem to be completely disconnected. Moreover, they have emerged from two totally independent realms. Historically, networkers have never cared about what is connected to their networks. At least, they have never get into the details on what was attached to the network. In the same way, IT specialists never cared too much about the network internals. This separated environment remained with the old Internet applications. However, nowadays the trend is changing and there is an IT and network convergence flow bringing together networks and clouds, or, in other words, converging the IT and network resources operation and management.

1.1.1 *Bringing Together Networks and Clouds*

Clouds are hardware-based services offering compute, network, and storage capacity. However, none of these common points mention the network, its availability or even the network resources

A deeper look at the definitions of Cloud computing in the research community shows that it is hard to find a uniform definition of the term, although most of them spin around the same base concepts. Vaquero et al. [VRmCL09] have stated "*clouds are a large pool of easily usable and accessible virtualized resources (such as hardware, development platforms and/or services). These resources can be dynamically reconfigured to adjust to a variable load (scale), allowing also for an optimum resource utilization. This pool of resources is typically exploited by a pay-per-use model in which guarantees are offered by the Infrastructure Provider by means of customized Service Legal Agreements (SLAs)*".

A McKinsey and Co. report [McK09] claims that "*Clouds are hardware-based services offering compute, network, and storage capacity where: Hardware management is highly abstracted from the buyer, buyers incur infrastructure costs as variable Operational Expenditures (OPEX), and infrastructure capacity is highly elastic*". A report from the University of California Berkeley [AFG+09] summarized the key characteristics of cloud computing as: " *(i) the illusion of infinite computing resources; (ii) the elimination of an up-front commitment by cloud users; and (iii) the ability to pay for use... as needed...*".

The National Institute of Standards and Technology (NIST) characterizes cloud computing [MG09] as "*... a pay-per-use model for enabling available, convenient, on-demand network access to a shared pool of configurable convenient, on-demand network access to a shared pool of configurable computing resources that can be rapidly provisioned and released with minimal management effort or service provider interaction*".

While there are countless other definitions, there seems to be common characteristics, which a cloud should have: (i) pay-per-use (no ongoing commitment), utility prices); (ii) elastic capacity and the illusion of infinite resources; (iii) self-service interface; and (iv) resources that are abstracted or virtualized [BBG11]. However, none of these common points mention the network, its availability or even the network resources. Analysis predict that in 2020, more than 80% of the IT will be outsourced within the Cloud [Nel10]. Clouds are revolutionizing the IT world, but treat the Internet or the network as always available, without constraints and absolutely reliable.

A set of critical applications and new emerging ones demand a highly reliable, robust and secure network. Apart, there are many infrastructure challenges on the arena in order to bring optical networks together with the Cloud such as the fact that there is a huge increase in the number of users/applications and a rapid increase in available bandwidth for users beyond 1Gbps; or that applications requesting 10Gbps connectivity are growing [DPC+10, ENJ+10].

Virtualization is seen as the process that will homogenize both IT and network resources through the provisioning of combined IT and network virtual infrastructures

The current trend to overcome the new challenges is a migration towards a full range and large-scale convergence of IT and network services. There are a lot of new applications offering remote IT resources interconnected through high-capacity networks. Some examples of these applications are Amazon virtualized server services[d], Microsoft Share Point[e] or BBCH HDTV broadcasting player - iPlayer[f]. There exists in the research community several initiatives aiming at developing novel end-to-end service provisioning mechanisms that automatically and efficiently bundles suitable IT resources with the required optical network connectivity services, and which provides them to the user in a single step and in an on demand manner.

1.1.2 *Virtualization: the Glue*

Virtualization is defined as the process consisting of building a virtual resource on top of one or several physical resources, depending on the selected paradigm: aggregation or partitioning [JT04]. From the networking perspective, over the recent years virtualization became a hot topic in networking research [SCB13], although the term is not new, neither for networking nor for IT. Virtual Private Networks (VPNs) represent an example of virtualization for security and business issues that have been in use for some time. The common idea behind virtualization is to enable the sharing of the same resources among different entities.

As a primary conclusion, both IT and network virtualization, through the abstraction of the physical devices as totally manageable, independent logical objects allow applications to easily deploy new services on top such virtualized infrastructures [GERL+10]. Ma-

d http://aws.amazon.com
e http://sharepoint.microsoft.com/
f http://www.bbc.co.uk/iplayer/

jor motivations to apply virtualization, and convert it as the glue for bringing together the *clouds* and the *networks* are cited in [FL09]; here follows the summary of those advantages:

- Lower infrastructure operational costs
- Enable new business models
- End-to-end cooperation among heterogeneous data plane technologies through virtualization (see Figure 1)
- Integrate heterogeneous hardware in applications with Service Oriented Architecture (SOA)
- End-to-end service orchestration involving network and IT resources
- Scale infrastructure on-demand
- Environmental impact (e.g. reduce energy consumption)

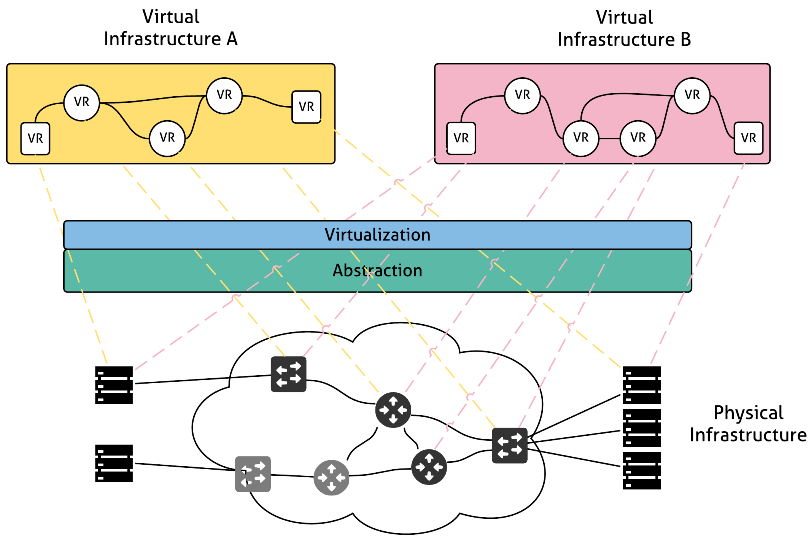

Figure 1: Example of physical infrastructure virtualization

However, in order to let network virtualization achieve the same level of maturity than the IT virtualization, there are still some major challenges to be faced. They are listed by the authors in [SCB13] as:

- **Interfacing**. Every infrastructure provider must provide an interface (there is yet no standard interface) in order to enable the virtual infrastructure operator to communicate and request for virtual infrastructures with specific characteristics.

- **Signaling and bootstrapping**. Before creating a virtual infrastructure, the operator of the virtual infrastructure must configure all the nodes in order to start the operation phase.
- **Resource and topology discovery**. In order to allocate resources for different requests, the infrastructure owners must be able to determine the topology of the networks they manage as well as the status of the corresponding network elements.
- **Resource allocation**. Efficient allocation and scheduling of physical resources among multiple virtual infrastructure requests is extremely important in order to maximize the number of co-existing virtual entities, and increase the utilization of the physical resources. Additionally, the allocation process, also known as virtual network embedding or mapping problem, can optimize any other metric, e.g. minimize the total energy consumption.
- **Admission control and usage policing**. The owner of the infrastructure, i.e. the infrastructure provider, must perform accurate accounting, and implement admission control and distributed usage policing algorithms to ensure that they can deliver the guaranteed performance, and the hosted virtual entities do not exceed allocated resources either locally or globally.
- **Mobility Management**. In a Network Virtualization Environment (NVE), mobility of the devices must be supported congenitally, not using makeshift solutions as in the existing Internet. Mobility in this context does not just refer to geographic mobility of the end-user devices, but also routers in the core network can move around using migration techniques.
- **Monitoring, configuration, and failure handling**. In order to enable the different virtual infrastructure operators to configure, monitor and control properly their virtual entities considerable changes at the level of network operations centres are required. Failures in the underlying physical substrate components can give rise to cascading series of failures in all the virtual networks.
- **Security and Privacy**. Isolation between coexisting virtual infrastructures can only provide a certain level of security and privacy, but it does not obviate the prevalent threats, intrusions, and attacks to the physical layer. For example, programmability of the different network elements can increase vulnerability if secure programming models and interfaces are unavailable.

Following the trends, as described up to the moment, and in order to fulfill new IT services' requirements, virtualization is seen as the process that will homogenize both IT and network resources through the provisioning of *combined IT and network virtual infrastructures*. In fact, the main interests in network virtualization are derived from the the virtualization applied to computers and its successful existence. It allows the usage optimization of the hardware devices, and therefore it actually avoids having an infrastructure with many equals devices performing less than 100% just because they have to be under different administrative domains [FL09].

The Internet, undoubtedly, is the most influential technical invention of the 20th century that affects and constantly changes all aspects of our day-to-day lives nowadays

Furthermore, network virtualization advocates also claim that due to the existence of multiple stakeholders with conflicting goals and policies, alterations to the existing Internet architecture are now limited to simple incremental updates; deployment of any new, radically different technology is next to impossible [CB10]. By introducing a plurality of heterogeneous network architectures cohabiting on a shared physical substrate, network virtualization promotes innovations and diversified applications. These last sentences bring us to the question on the future of the Internet, and what is the final goal of converging IT and network resources (and services).

The Internet, undoubtedly, is the most influential technical invention of the 20th century that affects and constantly changes all aspects of our day-to-day lives nowadays. Although it is hard to predict its long-term consequences, the once-separated worlds of media, entertainment, and communications have converged, with discrete, standalone services opening the door to an increased demand for blended, personalized, and customized services delivered to any device over any network. Network convergence with IT is nowadays one of the cornerstones of those services.

Therefore, in order to be respondent to strict cloud-based services and applications the networks along with converged IT solutions should still meet some vital requirements:

- **Tight integration of IT and connectivity technology resources**: the more intensive the cloud based services and applications become, the more essential the integration of IT and connectivity technologies, providing a pool of converged resources, becomes. For example the performance of highly interactive services being hosted over the cloud with intensive computational processes such as e-science, e-business, etc requires synchronized acceptable performance of inter dependant IT and network resources.

- **Resource volume and granularity**: cloud applications pose challenges in terms of the extensive and versatile amount of resources they require. Resources in need are a combination of IT (CPU, storage, or memory) and networking bandwidth and services. This means different service paradigms may need to coexist to enable resource allocations with appropriate granularity for a timely variant duration, while share a common underlying hardware infrastructure [DDLD+12], and [Hua12].

- **On-demand and rapid setup**: capability to support on-demand instantiation of the required network along with IT resources. The setup and tear-down of the optical/IT paths should be dynamic and rapid to maintain network efficiency and effectiveness, despite the frequency of requests for such applications or the connectivity duration requirements. This however is greatly challenging since it needs both suitable design and implementation as well as addressing interactive services such as in business/finance applications [Net12], and [DDLD+12].

- **Connection elasticity and scalability**: the resource consumption of a particular application may vary over time. This change can be caused by the resource utilization changes in each instance of the application, or a sheer increase in the number of users working with that application. Thus, the amount of resources tied to a particular application may clearly need to vary over time. This means that in addition to on-demand setup, the resource needs may vary during the lifetime of the application. So the network resource assignments should be elastic and scalable enough to vary with the allocated IT resources maintaining the performance quality and resource awareness [DDLD+12].

- **Resiliency**: as a primary and essential concern of any network / IT based service, the system should be highly agile to adopt contingencies in case of failures in the systems ingredients. For cloud based applications exploiting unified IT+network resources the process of failure detection and back up operations should be accurate and sufficiently fast in order to be able to maintain the network effectiveness in using the resources without compromising the users experience.

The inter-dependency of networking with IT management is critically important. It becomes crucial for the network to support the dynamism existing in the IT domain as much as possible

To facilitate convergence of optical networking with IT, the inter-dependency of networking with IT management is critically important. Therefore, it is crucial for the network to support the dynamism existing in the IT domain as much as possible. It should be highlighted that the aforementioned qualities of setup time, responsiveness to requests, the resiliency to possible malfunctions, the scalability and elasticity requirements for computational and bandwidth resources, etc. affect greatly the combined performance of network and IT operations.

1.1.3 *Wireless and wired convergence*

In the last years, the concept of mobile computing gained increased attention as it aims at supporting the additional requirement for ubiquitous access of mobile end users to computing resources. Mobile computing imposes the requirement that portable devices run standalone applications and/or accessing remote applications via wireless networks, moving computing power and data storage away from mobile devices to remote computing resources, according to the Mobile Cloud Computing (MCC) paradigm. It is true to say that continually more tablet PCs and smartphones are used for Web browsing, remote access to desktop applications, data sharing and mail services. MCC is described [DLNW13] as a new paradigm for mobile applications whereby the data processing and storage are moved from the mobile device to powerful and centralized computing platforms that can be located remotely (in the Cloud). These centralized applications are then accessed over wireless access networks based on a thin native client or web browser on the mobile devices. MCC is introduced as an integration of Cloud computing into the mobile environment and brings new types of services to mobile users. Advantages offered by the MCC include: i) dynamic on-demand provisioning and utilization of resources ii) improving data storage capacity and processing power by accessing remote computation resources through wireless access iii) improving reliability by the resilience mechanisms available in the Cloud and d) extending battery lifetime through computation offloading techniques enabling migration of large computations from resource-limited devices (i.e., mobile devices) to resourceful machines (i.e., servers in clouds).

Cross-domain, cross-technology virtualization for the creation of infrastructure slices involving converged wired and wireless domains as well as the IT resources comprehends the fundamental to be challenged in network convergence

These brings new requirements into the arena, which go far beyond simple wired network and IT convergence. In order to enable and support this emerging business opportunity, there is a need for a converged infrastructure supporting integrated wireless and wired high capacity networks, interconnecting IT resources in support of the Infrastructure as a Service (IaaS) paradigm as well as the Cloud and mobile Cloud computing paradigms [ATS13].

In this context, i.e. wired-wireless network integration, including fixed and mobile network technologies, there is a variety of technological challenges that need to be addressed. In order to ensure end-to-end connectivity through such multi-domain network, it is fundamental that communication takes place between the different protocol stacks involved. Typically, existing solutions are optimized for a specific network domain or segment, and its associated technology, with no overall network-wide view at all. Therefore, as traffic traverses the various network segments, each segment executes its own protocols and mechanisms to perform connection provisioning and resource allocation, introducing global inefficiencies. This implies thus that each specific segment may not provide an overall optimum solution supporting end-to-end connectivity, which at the end will have an impact on the overall solution adopted [ATS13].

When virtualization comes into the arena, this introduces one of the key challenges to be faced, being that of cross-domain and cross-technology virtualization for the creation of infrastructure slices that involve the converged wired and wireless domains as well as the IT resources with the aim to support the IaaS paradigm. Figure 2 depicts an example of such scenario. This comprehends the natural evolution of traditional data centres in which computing resources are provided and users are charged based on the utilization of computational resources, storage, and transfer of data. The appliance of virtualization over such multi-domain scenario facilitates sharing of the physical infrastructure among various virtual operators, at the same time it introduces new business models that suit well the nature and characteristics of the upcoming exploitation activities for the different stakeholders.

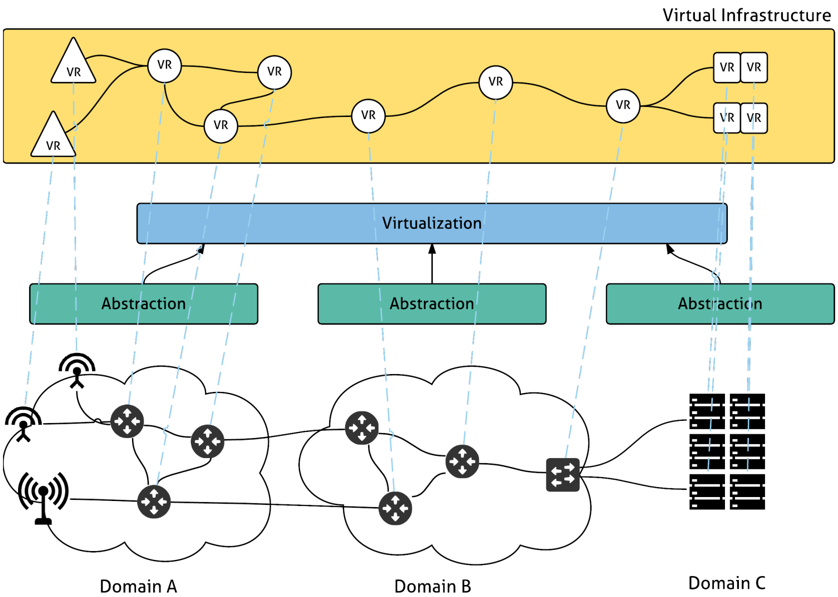

Figure 2: Example of cross-domain and cross-technology virtualization

Such an heterogeneous network and IT convergence involves the abstraction of the physical resources into logical resources that can then be assigned as independent entities to different virtual infrastructures and shared by a variety of virtual operators and end users. The objective here is thus to implement dynamically re-configurable unified virtual infrastructures over that heterogeneous infrastructures. These VIs must satisfy the virtual operators' requirements as well as the users' needs; while maintaining cost-effectiveness and other specific requirements such as energy efficiency.

There are representative voices in the community claiming that the benefits of such a seamless integration of wireless access, access-metro networks and IT resources under the umbrella of an integrated cross-domain virtualization layer would actively impact the creation of new business models or boost the business cases of current virtual network operators [YR11].

One of the examples is the Mobile Virtual Network Operator (MVNO). The MVNO have emerged as an interesting business and technological solution for both companies and customers. A MVNO provides services to the customers, but does not own the network assets such as the licensed frequency allocation of radio spectrum and the cell tower infrastructure. Instead, these assets are owned by the physical network infrastructure operators. The bursting of MVNOs in the telecommunications market has changed the mobile operator business to the extent of greatly benefiting the end users. By providing a greater number of operator solutions, market competition has been fostered, which results into lower mobile access price rates for the end customers.

MVNO have emerged as an interesting business and technological solution for both companies and customers, which represent a key example for wired-wireless convergence

Despite of the great success of the MVNOs, it is clear that some of these operators see their business opportunities quite restricted to the wireless access part of the network. Nowadays, the success of Internet is related to the consumption/generation of information and the thousands of applications built over such scope rather than just the simple network access [Jon11]. Therefore, it seems reasonable that operators cannot only focus on giving voice and data access services to increase their revenue. The provisioning of services associated to operating IT resources opens up new business and consumer opportunities to them.

The results of a fully-converged, and virtualized wired-wireless infrastructure including IT resources becomes a direct enabler of such new opportunities. It extends the operating range of mobile virtual network operators to own and operate virtual resources on the metro networks so as to bridge the gap between the wireless access and the computational infrastructure (i.e. thanks to the integrated virtualization architecture of wireless and wired networks, virtual operators will be able to access virtualized IT resources). This allows such operators to extend their service portfolio and provide to their customers new high-value services such as multimedia streaming or other virtual machine applications.

1.2 THE ERA OF SOFTWARIZATION

Once virtualization stepped into the arena, and was completely integrated into the new service delivery frameworks, including both wired/wireless and IT resources, a major breakthrough took place in the telecom arena for network control and management. Following the analogy of the IT systems, the era of abstraction and softwarization landed in the networking realm to stay and become one of the pillars for its evolution. The more convergence of resources was maturing, the more likely was the softwarization step to happen.

Computer networks are indeed complex and difficult to manage. These networks have many kinds of equipment, from routers and switches to middle boxes such as firewalls, networks address translators, server load balancers, or even intrusion detection systems. Routers and switches run complex, distributed control software that is typically closed and proprietary. The software implements network protocols that undergo years of standardization and interoperability testing. Network administrators typically configure individual network devices using configuration interfaces that vary across vendors and even across different products from the same vendor. Although some network management tools offer a central vantage point for configuring the network, these systems still operate at the level of individual protocols, mechanisms, and configuration interfaces. This mode of operation has slowed innovation, increased complexity, and inflated both the capital and operational costs of running a network [FRZ14, NMN+14].

SDN is changing the way we design and manage networks. Common interfaces for the operation of networking abstracted resources enable direct control over the state in the network's data plane elements

However, with the advent of the converged abstractions of different resources, and the creation of common interfaces for the operation of those resources, a novel trend emerged as the logical step in the way we design and manage networks. SDN is changing in fact the way we do that. SDN has two defining characteristics following the suggestion by the authors in [FRZ14]. First, an SDN separates the control plane (which decides how to handle the traffic) from the data plane (which forwards traffic according to decisions that the control plane makes). Second, an SDN consolidates the control plane, so that a single control program controls multiple data-plane elements. The SDN control plane exercises direct control over the state in the network's data-plane elements (i.e., routers, switches, and other middle boxes) via a well-defined Application Programming Interface (API) [FRZ14].

There is one organization behind the SDN adoption: the Open Networking Foundation (ONF). It is a user-driven organization dedicated to the promotion and adoption of SDN, and implementing SDN through open standards where such standards are necessary to move the networking industry forward [ONF12]. ONF defines SDN as an emerging architecture that is dynamic, manageable, cost-effective, and adaptable, making it ideal for the high-bandwidth, dynamic nature of today's applications. This architecture decouples the network control and forwarding functions enabling the network control to become directly programmable and the underlying infrastructure to be abstracted for applications and network services. The SDN architecture (see Figure 3), as defined by the ONF, is:

- **Directly programmable**: Network control is directly programmable because it is decoupled from forwarding functions.

- **Agile**: Abstracting control from forwarding lets administrators dynamically adjust network-wide traffic flow to meet changing needs.

- **Centrally managed**: Network intelligence is (logically) centralized in software-based SDN controllers that maintain a global view of the network, which appears to applications and policy engines as a single, logical switch.

- **Programmatically configured**: SDN lets network managers configure, manage, secure, and optimize network resources very quickly via dynamic, automated SDN programs, which they can write themselves because the programs do not depend on proprietary software.

- **Open standards-based and vendor-neutral**: When SDN is implemented by means of open standards, it simplifies network design and operation because instructions are provided by SDN controllers instead of multiple, vendor-specific devices and protocols.

As a result of the application of that SDN architecture, the network appears to the applications and policy engines as a single, logical switch. With SDN, enterprises and carriers gain vendor-independent control over the entire network from a single logical point, which greatly simplifies the network design and operation [ONF12]. SDN also greatly simplifies the network devices themselves, since they no longer need to understand and process thousands of protocols standards but merely accept instructions from the SDN controllers.

In addition to abstracting the network, SDN architectures support a set of APIs that make it possible to implement common network services, including routing, multicast, security, access control, bandwidth management, traffic engineering, or storage optimization, among others [ONF12].

Following the ONF guidelines, SDN addresses the fact that the static architecture of conventional networks is ill-suited to the dynamic computing and storage needs (Cloud computing needs) of today's environments. Computing paradigm trends driving the need for a new network paradigm includes:

- **Changing traffic patterns**: Applications that commonly access geographically distributed databases and servers through public and private clouds require extremely flexible traffic management and access to bandwidth on demand.

- **The "consumerization of IT"**: The Bring Your Own Device (BYOD) trend requires networks that are both flexible and secure.

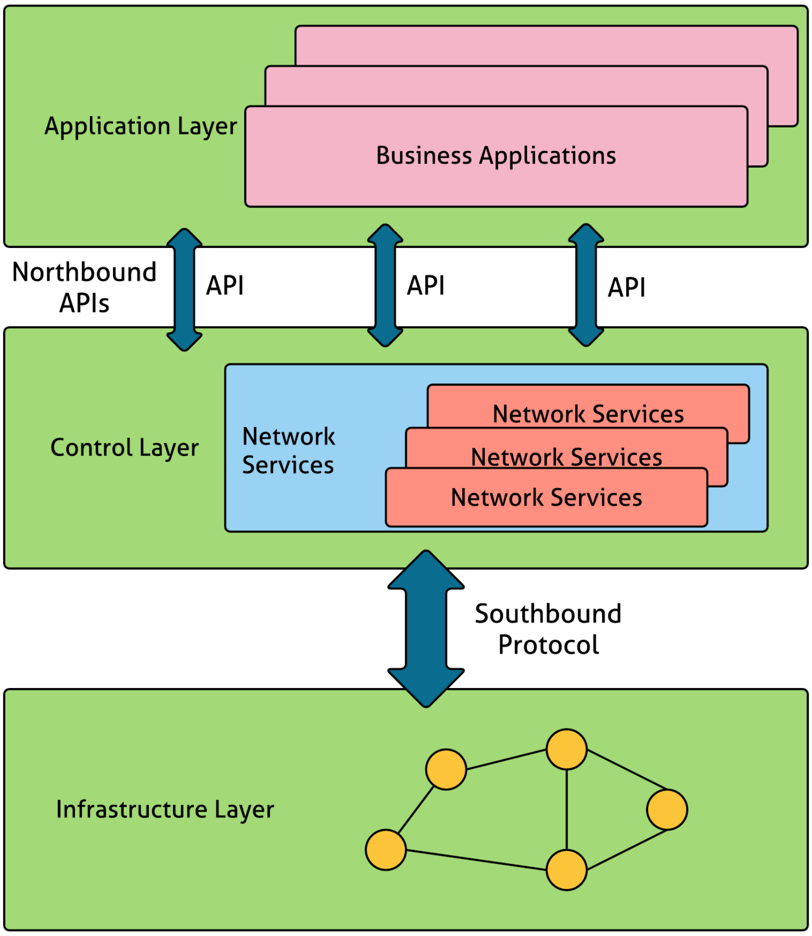

Figure 3: SDN architecture by ONF. Source [ONF12]

- **The rise of cloud services**: Users expect on-demand access to applications, infrastructure, and other IT resources.
- **Big data means more bandwidth**: Handling today's mega data sets requires massive parallel processing that is fueling a constant demand for additional capacity and any-to-any connectivity.

Virtualization and SDN are not the same; they may be based on abstraction processes, but they do not require each other to happen. However, a symbiosis between has emerged to maximize benefits

There is a misconception in the networking realm between network virtualization and SDN. Both approaches may be based on abstraction of the physical infrastructure, however, it becomes obvious that network virtualization does not require SDN to happen. In fact, it was there before the softwarization appeared into the arena. Similarly, SDN (the separation of a logically centralized control plane from the underlying data plane) does not imply network virtualization. Interestingly, however, a symbiosis between network virtualization and SDN has emerged, which has begun to catalyze several new research areas [NMN+14]. SDN and network virtualization related in three main ways:

- SDN as an enabling technology for network virtualization
- Network virtualization for evaluating and testing SDNs
- Virtualizing (slicing) an SDN

Authors in [NMN+14] clarify that *"people often refer to supposed benefits of SDN - such as amortizing the cost of physical resources or dynamically reconfiguring networks in multi-tenant environments - that actually come from network virtualization. Although SDN facilitates network virtualization through the common and unified resource abstractions and may thus make some of these functions easier to realize, it is important to recognize that the capabilities that SDN offers (i.e. the separation of data and control plane) do not directly provide these benefits"*.

1.3 VIRTUALIZATION OF NETWORK FUNCTIONS: THE NEXT STEP

NFV aims at virtualizing specific networking functions traditionally carried out by specialized hardware devices, and migrating them to software-based appliances deployed on top of commodity IT servers

With the advent of SDN technologies, based on the separation of the data and the control planes, a new generation of network programmable applications emerged [NMN+14]. They were built over the northbound APIs, homogenized by the corresponding controller using novel protocol. In November 2012, one of the European Telecommunication Standardization Institute (ETSI) working groups established itself as an Industry Specification Group and coined the term NFV, pushing the term virtualization one step further in the networking realm. It is a concept aimed at virtualizing network functions such as gateways, proxies, firewalls, and transcoders, traditionally carried out by specialized hardware devices, and migrating those functions to software-based appliances, deployed on top of commodity IT infrastructure. Following such approach, the migration of most of the in-network operations from hardware to software modules leads to various benefits including: (i) efficient management of hardware resources, (ii) rapid introduction of new network functions to the market, (iii) easy upgrade and maintenance, (iv) exploitation of existing virtualization and cloud management technologies for the Virtual Network Functions (VNFs), (v) significant Capital Expenditures (CAPEX) and OPEX reduction, (vi) enabling a wide variety of ecosystems; and (vii) encouraging openness within the ecosystem [NFV14].

However, even NFV seems to be a high-promising approach for the telecom industry and the service providers, it still faces certain challenges that could degrade its performance and hinder its implementation and deployment within the industry [HSMA14]. The major challenges identified in [HSMA14] for actual NFV-enabled deployments can be listed as: (i) security, (ii) computing performance,

(iii) interconnection of virtual network functions, (iv) portability, (v) operation and management, and (vi) carrier-grade service assurance. NFV incurs other well-defined risks, e.g., scalability in order to handle carrier network demands; management of both IT and network resources in support of network connectivity services and Network Functions (NFs) deployment; handling of network fault and management operations; Operational Support Systems (OSS)/Business Support Systems (BSS) backwards compatibility in migration situations; interoperability required to achieve end-to-end services offerings, including end-to-end Quality of Service (QoS). Essentially, software appliances should achieve performance comparable to their hardware counterparts.

ETSI NFV defines network services as entities composed of virtual network functions, which are the actual components performing the specific operations [NFV14]. In essence, NFV adds new capabilities to communication networks, but it requires a set of management and orchestration functions to be added at the current model of operations, administration, maintenance, and provisioning in order to meet the expected challenges and fulfill the carrier-grade requirements [NFV12b]. The virtualization insulates the network functions from the infrastructure resources, where they run both networking and computing through a common virtualization layer. This decoupling opens the door to the exposure of a new set of entities, adding new relationships between them and the Network Functions Virtualization Infrastructure (NFVI) where they are allocated and scheduled.

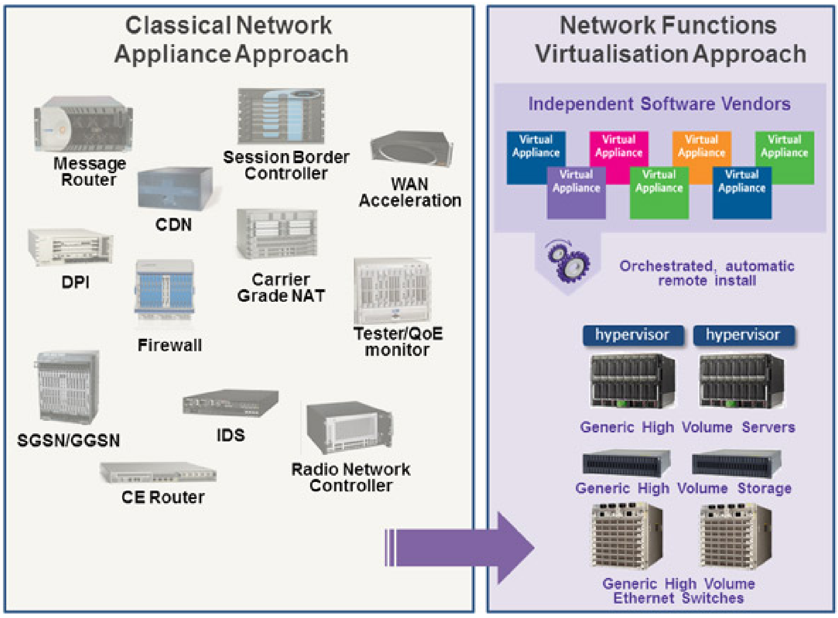

Figure 4: Overview of the NFV approach for telecom industry [Tel14]

NFV is a powerful emerging technique with widespread applicability. ETSI proposed a detailed list of high-level objectives of NFV [NFV14], which are:

- Improved capital efficiency compared with dedicated hardware implementations. This is achieved by using Commercial Off-The-Shelf (COTS) hardware (i.e. general purpose servers and storage devices) to provide NFs through software virtualization techniques. These network functions are referred as VNFs. Sharing of hardware and reducing the number of different hardware architectures in a network also contribute to this objective.

- Improved flexibility in assigning VNFs to hardware. This aids both scalability and largely decouples functionality from location, which allows software to be located at the most appropriate places, referred to in the present document as NFV Infrastructure - Point of Pressences (NFVI-PoPs) [NFV12a], e.g. at customers' premises, at network exchange points, in central offices, data centres, etc. This enables time of day reuse, support for test of alpha/beta and production versions, enhance resilience through virtualization, and facilitates resource sharing.

- Rapid service innovation through software-based service deployment.

- Improved operational efficiency resulting from common automation and operating procedures.

- Reduced power usage achieved by migrating workloads and powering down unused hardware.

- Standardized and open interfaces between virtualized network functions and the infrastructure and associated management entities so that such decoupled elements can be provided by different vendors.

In fact, ETSI defends that current networks are comprised of diverse network functions. These network functions are connected, or chained, in a certain way in order to achieve the desired overall functionality or service that the network is designed to provide. In non-virtualized networks, those NFs are implemented as a combination of vendor specific software and hardware, often referred to as network nodes or network elements. NFV represents a step forward for the diverse stakeholders in the telecommunication network environment. As such, NFV introduces a number of differences in the way network service provisioning is realized in comparison to current practices [NFV14]. Figure 4 depicts an example on how the different NFs of traditional networks will convert themselves into software appliances running over standard high-volume servers, enabling the set of advantages and benefits that are envisaged for the NFV trend.

Decoupling software from hardware: As the network element is no longer a collection of integrated hardware and software entities, the evolution of both are independent of each other. This enables the software to progress separately from the hardware, and vice versa.

Flexible network function deployment: The detachment of software from hardware helps reassign and share the infrastructure resources, thus together, hardware and software, can perform different functions at various times. Assuming that the pool of hardware or physical resources is already in place and installed at some NFVI-PoPs, the actual network function software instantiation can become more automated. Such automation leverages the different cloud and network technologies currently available. Also, this helps network operators deploy new network services faster over the same physical platform.

Dynamic operation: The decoupling of the functionality of the network function into instantiable software components provides greater flexibility to scale the actual VNF performance in a more dynamic way and with finer granularity, for instance, according to the actual traffic for which the network operator needs to provision capacity.

2 RELATED WORK

Respice post te! Hominem te esse memento!
- LATIN PROVERB

Historically, computer virtualization started in the early 60s, when the Multiple Access Computer (MAC) project got funded by the national science foundation. It aimed at providing hardware shared simultaneously by different users [ABCR66]. One of the most important reasons for introducing virtualization later then in the 1970s was to allow legacy software to run on expensive mainframe hardware. The software not only included various applications, but in fact also the operating systems they were deployed for [TS06]. The separation between having a single Central Processing Unit (CPU) and being able to pretend there are more can be extended to other resources as well, leading to what is known as resource virtualization.

Computer virtualization is not absolutely new; it started in the early 60s when IBM aimed at providing hardware shared simultaneously by different users

As hardware became cheaper, computers became more powerful, and the number of different operating system flavours was reducing, virtualization became less of an issue. However, matters have changed again since the late 1990s for several reasons. First, while hardware and low-level systems software change reasonably fast, software at higher levels of abstraction (e.g. middleware and applications), are much more stable. In other words, we are currently facing a situation where legacy software cannot be maintained at the same pace as the hardware platforms it relies on. Virtualization can help here by means of porting the legacy interfaces to new platforms and thus immediately opening up the latter for large classes of existing programs.

Equally important is the fact that networking has become completely pervasive. It is hard to imagine that a modern computer is not connected to a network. In practice, this connectivity requires that system administrators maintain a large and heterogeneous collection of server computers, each one running very different applications. Virtualization can help a lot: the diversity of platforms and machines can be reduced by essentially letting each application run on its own virtual machine. For example, in order to realize content delivery networks that can easily support replication of dynamic content, the authors in [AR02] argue that management becomes much easier if

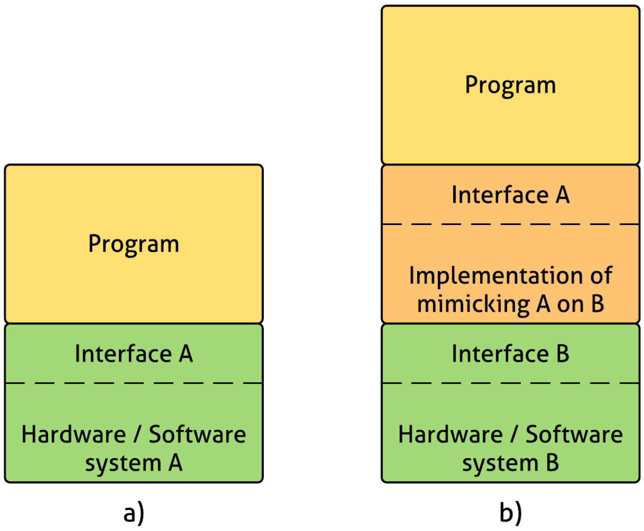

Figure 5: a) General organization between a program, interface, and system. b) General organization of virtualizing system A on top of system B [TS06]

edge servers would support virtualization. The virtualization concept is nowadays widely accepted and used into any commercial or production environment. However, in practice, there are many ways in which virtualization can be realized.

It is hard to imagine a computer not connected to the network

Several classifications on all the virtualization approaches have been performed. We will focus on the most representative. At the end, it is important to understand, as depicted in Figure 5 that the essence of virtualization is to mimic the behaviour of the physical resources, and therefore of the given interfaces.

In 1974, the authors in [PG74] classified two types of hypervisors[a], as depicted in Figure 6:

- Type 1 (or native, bare metal) hypervisors run directly on the host's hardware to control the hardware and to manage guest operating systems. A guest operating-system thus runs on another level above the hypervisor. This model represents the classic implementation of virtual-machine architectures
- Type 2 (or hosted) hypervisors run within a conventional operating-system environment. With the hypervisor layer as a distinct second software level, guest operating-systems run at the third level above the hardware. VirtualBox[b] represents a clear example of this approach

a A hypervisor is a piece of software that creates and runs virtual machines. The hypervisor manages the execution o the guests operating systems

b http://www.virtualbox.org

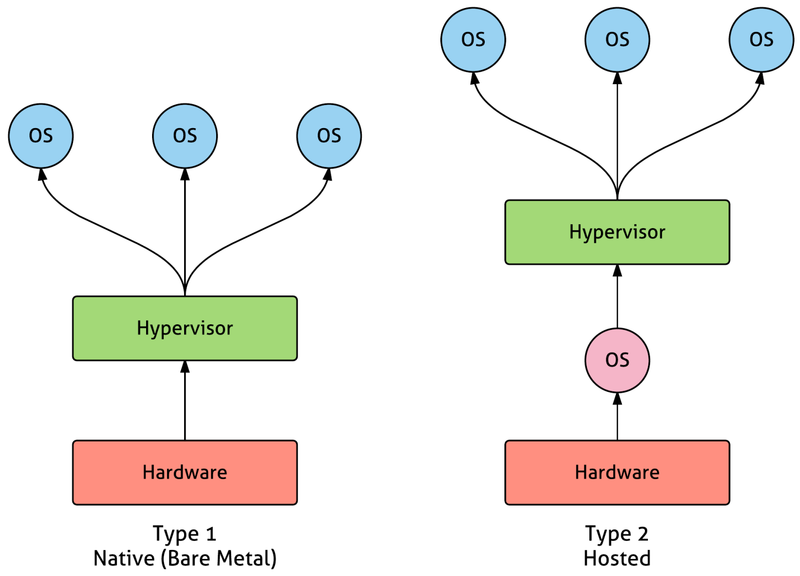

Figure 6: Classification of specific hypervisors implementations [PG74]

Additionally, in 2005, the authors in [SN05] provide also an overview of the different approaches. They state that in order to understand the differences in virtualization, it is important to realize that computer systems generally offer four different types of interfaces, at four different levels:

Virtualization targets to mimic the behaviour of a physical device or resource by means of interfaces which can be invoked by third-party entities

- An interface between the hardware and software, consisting of machine instructions that can be invoked by any program
- An interface between the hardware and software, consisting of machine instructions that can be invoked only by privileged programs (e.g. Operating System (OS))
- An interface consisting of system calls
- An interface consisting of library calls, generally forming an API.

Figure 7 depicts the distinct aforementioned interfaces. Virtualization can take place in two different ways. First, we can build a runtime system that essentially provides an abstract instruction set that is to be used for executing applications. Instructions can be interpreted, but could also be emulated as it is done for running Windows applications on UNIX platforms. This type of virtualization leads to what authors in [SN05] call a process virtual machine, stressing that virtualization is done essentially only for a single process.

An alternative approach towards virtualization is to provide a system that is essentially implemented as a layer completely shielding the original hardware, but offering the complete instructions set of

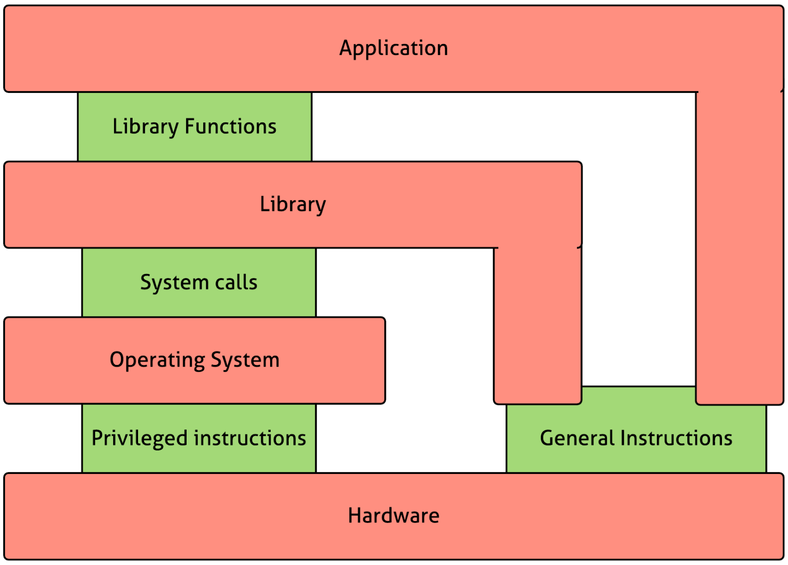

Figure 7: Various interfaces offered by computer systems [TS06]

that same (or other) hardware as an interface. It is crucial that this interface can be offered simultaneously to different programs. As a result, it is now possible to have multiple, and different operating systems run independently and concurrently on the same platform. The layer is generally referred to as a virtual machine monitor. Relationship between both classifications becomes sound and worth to mention when addressing network virtualization topic.

An alternative approach is to provide a system that is essentially implemented as a layer completely shielding the original hardware, but holding the same set of capabilities as the original hardware

Network virtualization is not yet as mature as computer systems virtualization. However, there are already several classifications for network virtualization. For example, authors in [SCB13] provided a classification of the approaches as a function of:

- The layer where the virtualization happens
- The resource that is virtualized: whether it is a node (including nodes from different technologies) or it is a link

Additionally, during the dissertation [GEFRFL12, ENJ+10, ENJ+11], we provided a generic definition of the different types of virtualization, using as a basis the initial virtualization classification that has been done within the IT realm, with the virtual machines. Therefore, we distinguish between two different types of virtualization, resource-based virtualization, which would become the equivalent to bare-metal virtualization, and service-based virtualization, which would be the equivalent at the Type 2 virtualization proposed in [PG74].

Resource-based virtualization (or resource virtualization) becomes the most suitable option in order to have the finest feasible granularity in any case, as well as the maximum level of flexibility to control

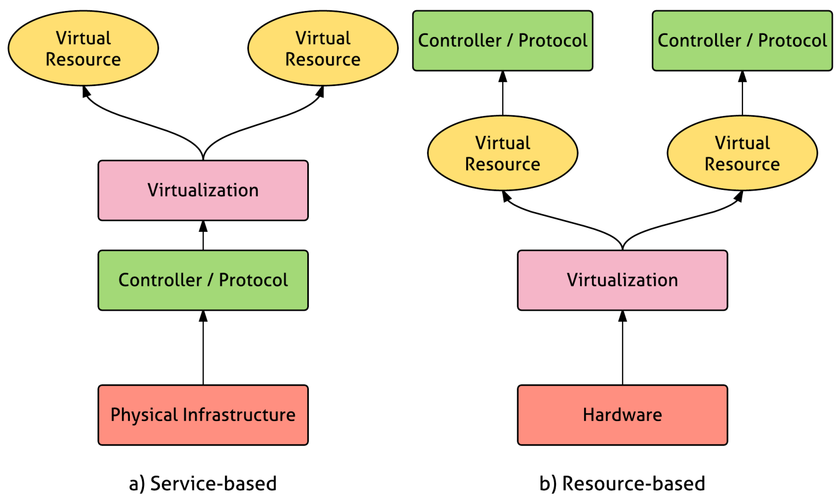

Figure 8: Service-based versus resource-based virtualization

the different virtual resources. However, in terms of implementation, the complexity of this approach increases, since it needs to completely control the physical resource itself. On the other hand, service-based virtualization loses part of the flexibility, since the virtualization system is located on top of the "network service".

Infrastructure virtualization can be classified in different categories, namely, partitioning, aggregation, abstraction, and transformation

As an example, the L3 VPN, should be an example of service-based virtualization, since the virtualization happens of top of the IP protocol. Granularity is also limited for this approach, since it depends on the northbound interface of the service itself. Thus, some information may be lost, causing also the lose of dynamism, granularity, and programmability of the virtualized resource. Both virtualization models have been deeply utilized to analyze requirements and architectural solutions in different international research activities, such as the European funded projects Generalised Architecture for Dynamic Infrastructure Services (GEYSERS) or Convergence of Wireless Optical Network Resources in support of Cloud services (CONTENT). Figure 8 depicts the different generic approaches to network virtualization.

2.1 INFRASTRUCTURE VIRTUALIZATION PARADIGMS

Additionally, infrastructure virtualization paradigms could be classified into two categories, namely, partitioning and aggregation [ENJ+11]. Partitioning refers to the technologies that enable multiple virtual infrastructures shares a same physical substrate. A simple example is to represent a wavelength into multiple virtual circuits with sub-wavelength granularity. On the other hand, aggregation refers to the technologies that represent multiple physical resources as a single virtual entity, for instance, multiple optical switches with fibre connec-

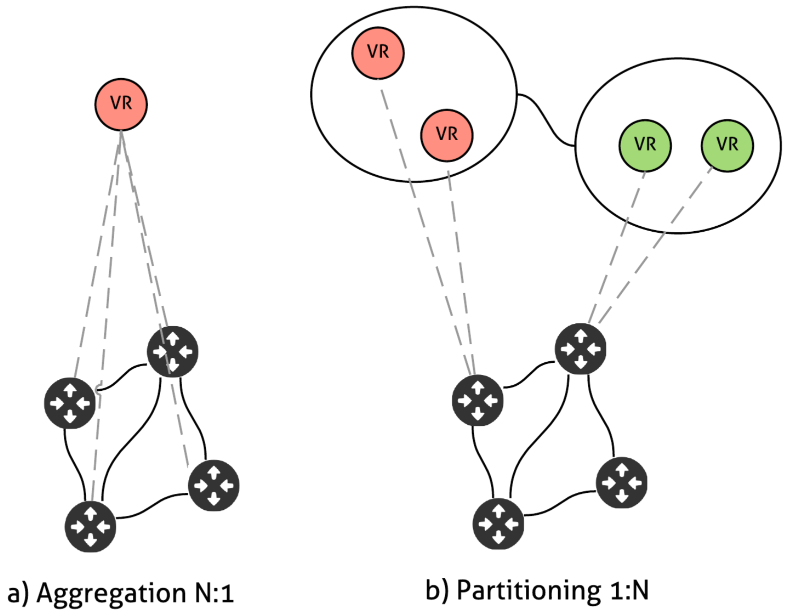

Figure 9: Typical infrastructure virtualization paradigms

tions can be represent as a single virtual node. These two categories, i.e., partitioning and aggregation, for network virtualization are also known as 1 : N Partitioning and N : 1 Aggregation, respectively. Various combination of these two categories have been also studied in the literature, for instance, 1 : 1 Abstraction is a special case of both virtualization types which simply abstract the physical resource as a virtual resource. Either partitioning or aggregation can be applied to different layers in a network, which enables a flexible network virtualization with various granularities. For example within optical networks, virtualization granularities include wavelength, sub-wavelength and a group of wavelengths. N : M Transformation is a special case of virtualization which combines both aggregation and partitioning.

Figures 9 and 10 depict respectively the different aforementioned infrastructure virtualization paradigms.

2.2 NETWORK VIRTUALIZATION

Virtualization is defined as the process consisting of building a virtual resource on top of one or several physical resources, depending on the selected paradigm: aggregation or partitioning [ENJ+10]. Network virtualization has been recently proposed as a very promising approach to overcome the current ossification of the Internet by allowing multiple heterogeneous virtual networks to co-exist on a shared physical infrastructure [APST05, TT05]. Networking researchers believe that virtualization should be a critical component of any next generation Internet architecture. Several challenges appear with the emergence of the network virtualization; however, we focus on the

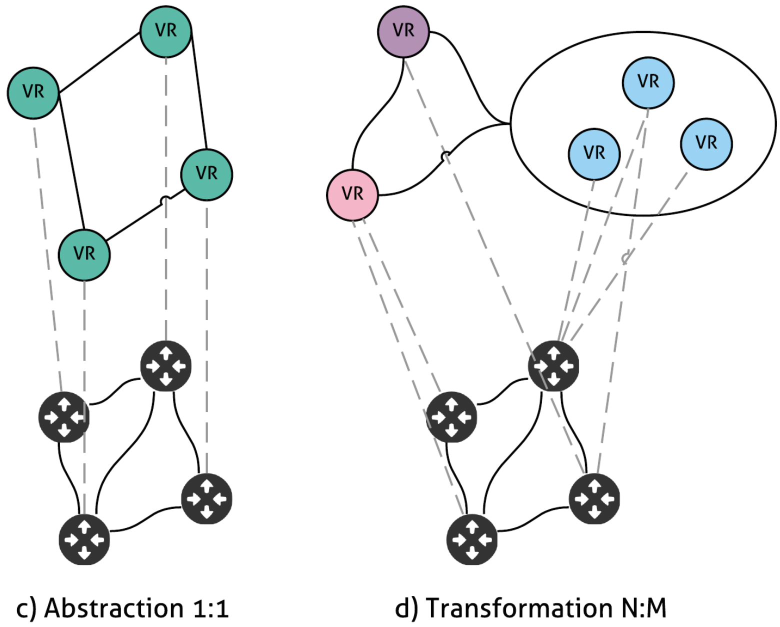

Figure 10: Extended infrastructure virtualization paradigms

well-known virtual network embedding problem, that basically deals with efficient mapping of virtual networks onto physical network resources. More specifically, for each virtual network creation request, the virtual network embedding is responsible for mapping the virtual nodes onto physical nodes and mapping virtual edges to physical links or paths, depending on the approach taken.

The basic graph theoretic problem underlying the Virtual Network Embedding (VNE) problem is actually NP-hard [Rah09], so most of the research on this problem has focused on approximation algorithms or fast heuristics. For example, in [ZA06], the authors proposed simple greedy heuristic algorithms for the VNE problem and developed some additional heuristics to speed up their algorithms. However, the term *virtual networks* has been extravagantly used by different research groups in order to describe their works on virtual private networks, overlay networks, and active or programmable networks. Until the late 2010s, very few of them actually followed the pluralist view of network virtualization [CB10].

There have been a lot of different approaches in the ecosystem of the VNE problem, each one considering different characteristics of the problem or trying to optimize different cost functions, from the pure theoretical point of view of the problem. Moreover, different research projects have built prototypes deployed on real scenarios that apart from the pure theoretical issues, have faced some problems such as underlying technology or the level of virtualization. In fact, through dynamic mapping of virtual resources onto physical hardware, the benefit gained from existing hardware can be maximized. Optimal dynamic resource allocation, leading to the self-configuration and organization of future networks, will be necessary to provide customized end-to-end guaranteed services to end users. This optimality can be computed with regard to different objectives, ranging from QoS, economical profit, or survivability over energy-efficiency to security of the networks [FBTB+13].

A lot of different approaches to the VNE problem have been proposed in the literature, each one considering different characteristics of the problem or trying to optimize different cost functions

Basically, VNE deals with the allocation of virtual resources both in nodes and links. Authors in [FBTB+13] propose to divide the problem in two sub-problems: Virtual Node Mapping (VNoM) where virtual nodes have to be allocated in physical nodes and Virtual Link Mapping (VLiM) where virtual links connecting nodes have to be mapped to paths connecting the corresponding nodes in the substrate network.

Authors in [WHL+14] provide a complete survey of existing VNE methods and algorithms within Cloud computing environments. However, the most complete survey on VNE is provided by the authors in [FBTB+13]. The authors provide a complete taxonomy for the virtual network embedding problem characterized by three constraints. Depending on the scenario, modification and relocation of virtual resources may be necessary. As such, VNE approaches either have to be static (i.e. with unchanging infrastructures) or dynamic (taking changes in virtual and substrate infrastructure into account). Moreover, virtual networks might be spread over the substrate infrastructure of multiple InPs. In this case, VNE has to be performed in a distributed way with multiple entities contributing to the mapping. Finally, depending on the scenario, virtual resources may be realized either concise, i.e. minimizing substrate resource usage, or redundant, combining multiple substrate resources to realize one virtual resource [FBTB+13].

Instead of a particular property of a VNE algorithm, these constraints are rather different variants of the underlying VNE problem. Thus, the authors propose that all VNE approaches proposed in the literature can be categorized according to whether they are Static or Dynamic, Centralized or Distributed, and Concise or Redundant.

Static vs. Dynamic: Typically, in real-world situations, virtualization has to be addressed as an online problem, i.e. virtual infrastructure requests will not be known in advance, they arrive to the system dynamically and can stay in the network for an arbitrary amount of time. On the other way around, offline VNE means that all the requests are known in advance and can be addressed all together. While in principle, all approaches can be operated in an online manner, static VNE approaches do not contemplate the possibility of remapping one of more requests to improve the performance of the embedding in the underlying network. Dynamic embedding approaches try to reconfigure the mapped virtual resources in order to reorganize the resource allocation and optimize the utilization of resources. Service disruption needs to be also considered in those scenarios [RTA+14].

Centralized vs. Distributed: The problem can be solved in either a centralized, i.e. there will be one entity which is responsible for performing the allocation, or in a distributed way, i.e. it utilizes multiple entities in parallel for computing the embeddings.

Concise vs. Redundant: A failure of a single substrate entity will affect all virtual entities that are mapped upon it. Therefore, in environments where fault-sensitive applications are deployed inside the virtual networks, it can be advisable to set-up backup resources that can be used as fall-back resources in case the corresponding primary resources fail. To do that, the embedding result itself can be redundant to be resilient regarding node and/or link failures. Otherwise, the embedding result is referred to be "concise" if there is no redundancy.

The authors in the survey [FBTB+13] analyze more than one hundred different approaches to virtualization up to 2013 following the aforementioned taxonomy. Wireless network virtualization is still addressed as a future activity, and thus no wired wireless convergence is addressed in the article. For further details on the classification please refer to [FBTB+13].

Optical network virtualization utilizes the concepts of infrastructure virtualization, i.e. aggregation, partitioning, and abstraction over optical node and link resources

2.3 OPTICAL NETWORKS VIRTUALIZATION

Optical network virtualization enables network operators to generate Virtual Optical Networks (VONs) over the same physical infrastructure, which operate and function concurrently and separately [PNA+11].

The flexibility and transparency for the optical network infrastructures enabled by virtualization, along with the capability to provide open interfaces and Application Programming Interfaces, allows the network to be programmed to deliver services agnostic to the technology running in the physical layer [FSP+12].

Optical network virtualization in general utilizes the concepts of abstraction, partitioning, and aggregation over node and link resources to realize a logical representation of network(s) over the physical resources. By resource abstraction operators are able to extract the capabilities of the underlying technologies and use them for planning the partitioning and aggregation. By partitioning, the physical resources available are shared among multiple users in a way that the small divisions can demonstrate the fundamental functionalities of the physical elements while their operation is isolated from one to another. The aggregation approach performs the opposite function, in which several physical resources are bundled and used as a single unit seamlessly. In a network, nodes can be aggregated to enable more functionality, increased data rate, or improve processing power, as one unit. Links being wavelengths or fibres can also be virtually aggregated to present a logical link of greater capacity. The aggregation or partitioning procedures are bound to the hardware capabilities and physical attributes of the elements and the network.

Virtualization of networks elements of nodes and links according to different authors, i.e.[NEPS11], [ENJ+11], and [EPN+11] are described in the following paragraphs.

Optical node virtualization is a procedure that enables the representation of the optical nodes as virtual instances of physical optical devices, inheriting critical characteristics of the physical layer. It relies on either the partitioning of a single optical node or the aggregation of multiple optical nodes.

Virtualization techniques for different types of optical networks of different technologies and granularities may vary, as the node and link characteristics are going to vary in each particular network

Optical link virtualization consists of abstracting optical data links as virtual instances by partitioning or aggregation. The partitioning of optical data links is introduced by dividing the link capacity into smaller units, resulting in the granularities of sub-wavelength and wavelength over fibre links while the aggregation results in a granularity of waveband (or fibre or group of fibres). Optical Link virtualization is bound to the capabilities/ technologies of the nodes interconnected using the links.

Virtualization techniques for different types of optical networks of different technologies and granularities may vary, as the node and link characteristics are going to vary in each particular network. For example, in a wavelength switched network with Optical Cross Connects (OXCs) and Reconfigurable Optical Add-Drop Multiplexers (ROADMs) virtualization approaches, achievable granularities, and hence the administration of the network slices are different from networks with sub-wavelength granularity of switching and control, and so on.

Optical sub-lambda network virtualization. Optical sub-wavelength networking is a very promising approach in efficient exploitation of the available capacity in WDM links [HSJ+11]. Sub-wavelength networks allow access to fine granularities of resources over the wavelengths, using a portion of the huge available bandwidth, saving the remaining to be filled up by new connection requests. This mechanism is of great importance especially for networks exposed to low/medium bit rate paths with sheer amount of requests. As a use case scenario, in edge and access areas where the traffic demands are from individual users or small enterprises, optical sub-wavelength switching provides connectivity and network services to individual requests using the available capacity in a very efficient manner [HSJ+11].

Meanwhile, these networks intrinsically are network virtualization enablers in a sense that they provide control of very fine granularity of network resources. Adopting virtualization techniques on the other hand can highly leverage the usability of such networks by allowing several operators to operate independently over the same infrastructure without interfering with one another. This will enable realizing networks as a service with great flexibility in defining the network characteristics highly suitable for new business models with multiple operators and service providers.

Initial work on optical routers and switches was performed by Qiao [QY99] in the context of the Optical Burst Switching (OBS)) proposal. OBS proposed a hybrid electro optical approach to control and transport data supporting some of the capabilities of Optical Packet Switching (OPS) but at the same time limiting some of the challenging technology requirements in terms of optical buffering, optical processing, and very fast optical switching.

This effort has lead to some very interesting research and prototype developments, such as an OBS ring test-bed in [DCM+11], the Optical Packet Switch and Transport (OPST) network solution by the authors within [Net11], or even the Time-driven Switched Optical Network (TSON) sub wavelength switching by [ZTA+11]. All these efforts however, take on different approaches to tackle the complexities and technical challenges. These systems use various provisioning mechanisms and resource allocation schemes, exploiting different connectivity patterns and hardware. This means that virtualizing any of these emerging networks needs to be addressed for each specific network implementation.

Sub-wavelength switching also is enabled by using Optical Orthogonal Frequency Division Multiple Access (OOFDMA) solutions, as explained in details by the authors within [JTK+09]. The Optical Orthogonal Frequency Division Multiplexing (OOFDM) sub-wavelength solution offers great flexibility in data rates and modulation levels, however the technology is still in its infancy to be properly deployed in a network environment.

Sub-wavelength networks allow access to fine granularities of resources over the wavelengths, using a portion of the huge available bandwidth, saving the remaining to be filled up by new connection requests

Time Division Multiple Access (TDMA)-based Optical sub-lambda virtualization. Time Division Multiplexing (TDM) based sub-wavelength switching systems use sliced time frames, over which each time slice represents a unit of resource, carrying bursts of data, and are allocated individually or as a group to satisfy the communication requirements. OBS, slotted OBS, Labeled Optical Burst Switching (LOBS) [GOQSG+10], or TSON are the proposed mechanisms, which use this approach. OBS solutions tend to offer a more realistic method for implementing time shared sub-wavelength switching systems from a practical point of view and enabling technologies, as compared to pure OPS solutions.

Link virtualization: each link in TSON is comprised of a single Single-mode Fibre (SMF) with multiple wavelengths available per fibre. The wavelengths are used to transfer data with variable rates by allocating time slots across them for each light path. If a wavelength supports data rate x (TSON uses 10Gb/s Small Form-factor Pluggable + (SFP+)

transponders), by slicing it up to a number of time slots repeating in each frame, the granularity of data rate equivalent to the duration of a time slot can be realized. So TSON with 100 time slots over a 10Gb/s link, it will provide 100 Mb/s as the minimum bandwidth level achievable for any end-to-end communication. For setting up virtualized links, each network slice can be allocated as small as 1 time slot per link, (100 Mb/s). The time slice can be located on any of the wavelength in the fibre link. In case of requiring slices to make an aggregated bandwidth, the time slot units over one or multiple wavelength can be allocated. The time slots are not obliged to be adjacently located. The physical elements can be used as isolated resources are: fibres, wavelengths, or time units. Regarding the possible limitations on virtualization services over TSON network, the allocation when making aggregated services should consider time slot and wavelength continuity constraints. Regarding the reach of these networks, transmission can be limited by impairments such as loss and dispersion, so elements such as amplifiers or dispersion compensation modules need to be considered when composing services in TSON network.

Node virtualization: the nodes usually included in the burst switched networks can be categorized in to two types: (i) edge nodes, and (ii) core nodes.

Edge nodes: these nodes are placed in the border of the subwavelength networks interfacing the other technology domains. These nodes must take care of traffic classification, traffic mapping and conversion, as well as QoS handling for the ingress traffic. In this process, the nodes should support logical slice-ability of components so that multiple instances of virtualized nodes can be realized for operations and transmission.

TDMA-based sub-wavelength switching systems use sliced time frames, over which each time slice represents a unit of resource, carrying bursts of data, and are allocated individually or as a group to satisfy the communication requirements

Core nodes: In the core of the network, the switching most prominently and desirably takes place by transparent fast switches. These switches need to be controlled to operate on very fine time granularities of nano/pico second scales to divert/isolate the streams of traffic.

In general, the virtualization of time based sub wavelength switched paths using switching nodes is dependent on the way these devices are controlled by the control mechanisms and resource allocation elements.

2.3.1 *Optical networks technological solutions for cloud*

Commercially available systems support transmission speed of 100 Gbps for a few of years now, while research supporting transmission at 400 Gbps or even 1 Tbps is already in progress [GJLY12, Com12]. Currently WDM based technologies have already been extensively deployed in the network core and in metropolitan areas [JS11] offering great amount of spectral capacity by simultaneous transmission of as many as 200 channels of 50 GHz across the C and L bands using commercial transceivers with bit rates reaching to 100 Gbps recently is possible.

Apart of wavelength based transmissions, research on enabling super channels using flexi grid/ grid less, multi-mode, multi tone, and Photonic Integrated Circuits (PIC) based transmission systems is ongoing. These advancements in optical networks are transforming the static and rigid structure of optical systems into flexible and more elastic environments. In the data plane, FlexiGrid and Gridless solutions promise great flexibility in bandwidth support, by releasing the trapped capacity imposed by the channel Grids. These channel grids cause great inefficiencies on idle channels and thus restrictions to achieve higher line rates. The FlexiGrid and/or Gridless technologies capabilities in enabling super channels [Net12] are of vital application for edge networks when directing vast amount of data between data centres.

On the other hand elastic optical networking and Grid-less communication systems have been proposed to transmit and switch data channels beyond 100 Gbps [DDLD+12, JTK+09]. They are based on an optical networking architecture called SLICE, with a new acPCE, which computes paths based on Orthogonal Frequency Division Multiplexing (OFDM) transponders and modulation formats, and then filters the assigned bandwidth for achieving just enough spectrum assignment for the required reach. The same authors in [JOS+10] provide a comprehensive look at elastic networking and elaborate on the use of ROADMs and OFDM transponders in which the centre frequency and the spectral width become key variables. In addition [GJLY12] and [MCM11] study the flexible grid and elastic networking integrated with Generalised Multi-Protocol Label Switching (GMPLS) control plane.

In fact, optical networks are undergoing significant changes, fueled by the exponential growth of traffic due to multimedia services and by the increased uncertainty in predicting the sources of this traffic due to the ever changing models of content providers over the Internet. To properly address this challenge, one needs flexible and adaptive networks equipped with flexible transceivers and network elements that can adapt to the actual traffic needs. The combination of adaptive transceivers, a flexible grid, and intelligent client nodes enables a new elastic networking paradigm [JTK+09], allowing service providers to address the increasing needs of the network without frequently overhauling it. This new approach is called elastic optical networking, whereby the term elastic refers to two fundamental properties [GJLY12]:

- the optical spectrum can be divided up flexibly

- the transceivers can generate elastic optical paths; that is, paths with variable bit rates

Moreover the rising deployments of optical burst and packet switching technologies [ZRY+12, DCM+11] for core, metro areas of the networks, allow control and utilization of smaller dividends of fibre/wavelength links capacity in comparison to circuit switched technologies such as WDM. This facilitates virtualization and other cloud enabler technologies over optical networks, while boosting the effectiveness in using the great capacity existing per fibre for providing diverse range of services.

In time-based sub-wavelength switching, OBS and OPS systems are amongst the ones extensively studied. OBS systems, despite their shortcomings in providing guaranteed performances for various traffic types, due to their more feasible implementation prospective have constantly experienced architectural refinements and architectural extensions. For example, Time-Driven Switched Optical Networks [VMTP11] and Labeled OBS with Home circuits (LOBS-H) [GOQSG+10] have been proposed to improve the total throughput of OBS system. Also mechanisms such as burst buffering with bre delay lines [LM03], burst deection routing [WMA00], burst segmentation [VJS02], and burst cloning [HVJ05, GOSGLALG11], cognitive QoS approaches [Elb11] have been also proposed for improved OBS based architectures. However, these schemes increase the network complexity and cannot absolutely provide lossless networking paradigms. OBS systems with aid of external control planes such as GMPLS for in-advance and on-demand data transfer seem to be very promising, as [QWL06] gives studies over OBS and GMPLS extended signalling. Authors in [PCC+08] report on initial activities towards GMPLS signalling extensions to support OBS. However they do not aim to eliminate the critical contention. [PSCJ09] provides theoretical studies over integration of GMPLS and OBS with contention avoidance. Additionally, [LGT+12] reports on theoretical studies on OBS/Wavelength Switched Optical Networks (WSON) controlled networks with different Transfer Control Protocol (TCP) protocols for grid applications.

In the access on the other side, Passive Optical Network (PON) based technologies already allow inexpensive yet great bandwidth support (up to 1Gbps) by using TDMA of traffic to the end users. Also the use of sub wavelength switched networks is being stretched out more to the user ends since they provide sharing of resources for serving multitude of low/medium rate consumers, in a more controllable way.

2.3.2 *Optical technologies for cloud networking*

Cloud based applications, network centric services and consumers such as e-science, e-government, e-business apps, Video on Demand

(VoD) or Game on Demand (GoD), and data centric operations of virtualized PCs, Storage Area Network (SAN), or data replication have transformed traditional Data Centres (DCs) to massive scale computing infrastructures [Rea12, LLK+10, VLZJ11] with highly complex interconnectivity requirements guaranteeing any-to-any server communications with stringent QoS requirements. Data Centres as the main propellers of the ultimate everything in the cloud with existing and increasing responsibilities in storing, processing, rendering, searching and so on, should employ highly effective intra/inter networking in terms of connectivity, bandwidth and latency in order to make the services to the end users seamlessly fast with the highest quality of experience possible.

This is whilst the current most deployed hierarchical opaque L2/L3 DC networks impose scalability restrictions, resource inefficiency, non-optimal QoS and limited resiliency in delivering future application services [EN11]. As such, future applications could benefit from flexible ultra-low latency finely granular optical network technologies able to integrate seamless provisioning of combined intra/inter DC cloud-based computing and network services [YYW12]. Such a network could deliver enhanced resource usage efficiency and network scalability.

2.4 WIRELESS TECHNOLOGIES VIRTUALIZATION

In the wireless medium, radio resources can be shared and thus virtualized in different ways such as in time, space, and frequency

In the wireless medium, radio resources can be shared and thus virtualized in different ways such as in time, space, and frequency. By splitting the wireless medium into different channels, to each channel a specific time slot (Time Division Multiplexing), space (Space Division Multiplexing), frequency (Frequency Division Multiplexing) or combinations can be allocated [AE11a, SB08]. To conserve frequency channels, virtualization of the wireless medium uses the same radio frequency for multiple virtual interfaces, each with its own Service Set Identifier (SSID) or network name. Efforts also have been made in splitting the wireless medium by assigning different radio frequency channels to the virtual interfaces or operators [SHSR08, PCM09].

In general, virtualization of the wireless domain and slicing can take place in the physical layer, Data-link layer (with virtual Mac addressing schemes and open source driver manipulation) or network layer (VLAN, VPN, label switching). Initially we focus in the first two, while we present the state of the art research on layer 3 virtualization of the wireless domain in the following.

Virtualization slicing technologies of the wireless medium are the following [PS06]:

- **Frequency Division Multiple Access (FDMA)**: Virtualize a node by partitioning the frequencies. There can be as many as 12 virtual nodes in a single physical 802.11a node where each virtual node is allocated a single frequency. Although a node can be partitioned (into virtual nodes) along the frequency dimension, switching from one virtual node to another is not instantaneous. Channel switching time for Atheros cards is 5ms while that for Intel cards is 20 ms.

- **TDMA**: Virtualize a node by partitioning along the time dimension. That is, different users get to use a given frequency partition in different "time slots". For example, an 802.11a node can be logically partitioned into 3 virtual nodes by allocating 3 non-overlapping time slots to three users.
- **Frequency Hopping (FH)**: A node can be virtualized by allowing different users to use different frequency partitions at different time-slots, i.e. frequency hopping.
- **Code Division Multiple Access (CDMA)**: Virtualize a node by partitioning in "code" dimension. This applies to base stations that operate using orthogonal codes.
- **Space Division Multiple Access (SDMA)**: In this technique, a full node is allocated to a given user.

Virtualization and slicing refers to combinations of SDMA with TDMA or FDMA or hybrid schemes with combined SDMA, FDMA and TDMA: in the technique SDMA-TDMA, a grid of nodes is partitioned using spatial separation, and the spatial slices are further partitioned in the time dimension by creating time slots.

2.4.1 *Virtual Access Points in the 802.11 family*

In [BVSR10] the SplitAP architecture is proposed in order for a single wireless access point to emulate multiple virtual access points. Clients from different networks associate with corresponding virtual Access Points (APs) through the use of the same underlying hardware. Isolation across groups of wireless users is provided through airtime control at the clients based on the information provided by the SplitAP controller running at the AP that is used to compute slice airtime usage time per virtual AP. In [AE11b] the approach of creating multiple virtual wireless networks through one physical wireless LAN interface, so that each virtual machine has its own wireless network is proposed. Available open source solutions such as KVM[c] , or hostapd[d] provide the software infrastructure to deploy and implement such an approach on Linux OS. In [AE11a] emulation of the MAC layer is again used with KVM as back-end for virtualization.

c http://www.linux-kvm.org
d https://w1.fi/hostapd/

2.4.2 *Base Station Virtualization - LTE and 802.16 networks*

Significant work in the area of Worldwide Interoperability for Microwave Access (WiMAX) base station virtualization is done in the series of papers [BSZ+11, BSMR10, BDSR10, BSR12a, BSR12b]. In this work, base-station virtualization is considered from two perspectives:

- from the perspective of a mobile virtual network operator that lease the physical network from a mobile network operator; and
- from a test-bed perspective where, in order to support shared end to end experiments, the wireless edge is shared among multiple experimental slices.

Within every slice the proposed virtual base-station framework provides a network device, which acts as an interface on an actual base-station. Every frame directed to this interface transparently reaches the WiMAX clients through the physical base-station. Virtualization of the WiMAX radio itself is considered including important sub-components such as the WiMAX MAC scheduler, service flows, and the time-frequency slots of the spectrum used by that scheduler for sharing across slices.

Besides of the proposed architecture in [BSZ+11, BSR12a], a very interesting approach can be found in the L2 data-path mechanism required for forwarding frames from the virtual Base Stations (BSTs) to the physical base-station. In [BSR12b] instead of using layer-2 forwarding, the authors propose tunnelling all layer-2 frames over a layer-3 based IP network. This mechanism also allows us to geographically decouple the virtual BTS substrate and the WiMAX ASN-Gateway. Finally we mention that in [BZR11] the authors show how the wireless virtual network mapping problem can be simplified and be used instead as a mechanism for provisioning wireless points of presences as additions to conventional cellular voice and data services.

In the same direction in [KMZR13] the Cellslice is proposed that focuses on deployments with shared-spectrum Radio Access Network (RAN) sharing. The design of CellSlice is oblivious to a particular cellular technology and is equally applicable to Long Term Evolution (LTE), Long Term Evolution - Advanced (LTE-A) and WiMAX. CellSlice adopts the design of Network Virtualization Substrate (NVS) for the downlink also proposed by authors in [KMZR12a] but indirectly constrains the uplink scheduler's decisions using a simple feedback-based adaptation algorithm. In [KMZR12b] virtualization techniques of a cellular base-station lead to US patent.

Virtualization for the Cellular network case is also examined in [FMD11] and [DPGZ11] while a commercial solution is OpenBTS[e].

e http://openbts.org

MultiRAN operators can minimize their expenses by sharing the costs of cellular sites and equipment, while continuing to offer differentiated services, while OpenBTS replaces the conventional Global System for Mobile communications (GSM) operator core network infrastructure from layer 3 upwards. Instead of relying on external base station controllers for radio resource management, OpenBTS units perform this function internally. Instead of forwarding call traffic through to an operator's mobile switching center, OpenBTS delivers calls via Session Initiation Protocol (SIP) to a Voice over IP (VoIP) soft switch.

2.4.3 *Cognitive Radios*

Another technique used for virtualization in MVNO scenarios is the technique of Cognitive radios. A cognitive radio is a transceiver which automatically detects available channels in wireless spectrum and accordingly changes its transmission or reception parameters so more wireless communications may run concurrently in a given spectrum band at a place. In [NIM+11] AMPHIBIA a Cognitive Virtualization Platform is proposed that enables end-to-end slicing over wired and wireless networks.

2.5 SOFTWARE-DEFINED NETWORKING

The idea of programmable networks has recently re-gained considerable momentum, as introduced in Chapter 1, due to the emergence of the SDN approach. It promises to dramatically simplify network control and management, at the same time it boosts innovation on top of networking infrastructures. The field of SDN is quite recent, yet growing at a very fast pace [NMN+14]. There are several activities within the community around the SDN topic.

The idea of programmable networks has recently re-gained considerable momentum due to the emergence of the SDN approach

Authors in [KRV+14] provide, among others, a brief history of software-defined networking. They state that SDN leverages on networking ideas with a longer history[NMN+14]. In particular, it builds on work made on programmable networks, such as active networks [TSS+97], programmable Asynchronous Transfer Mode (ATM) networks [LLM96, Laz97], and on proposals for control and data plane separation, such as the network control point [HSS82] and routing control platform [CCF+05].

In fact, active networks [TSS+97] represent one of the early attempts on building new network architectures based on this dynamic concept. The idea behind those networks is for each node to be capable of performing computations on the different packets traversing the data plane. ForCES [DSH+10], OpenFlow [MAB+08], and POF [Son13] comprehend most recent approaches for designing and deploying programmable data plane devices. Instead of directly modifying the packets or their content, these new proposals rely on the modification of the forwarding devices in order to support flow tables, which can then be dynamically configured.

Figure below (Fig. 11) summarizes a bottom-up approach in order to survey the current activities within SDN[KRV+14]. For each colored box in the there are hundreds of different activities within the community, which will not be listed in this section for the sake of readability. For a complete SDN survey the user is referred to [NMN+14, KRV+14, FRZ14].

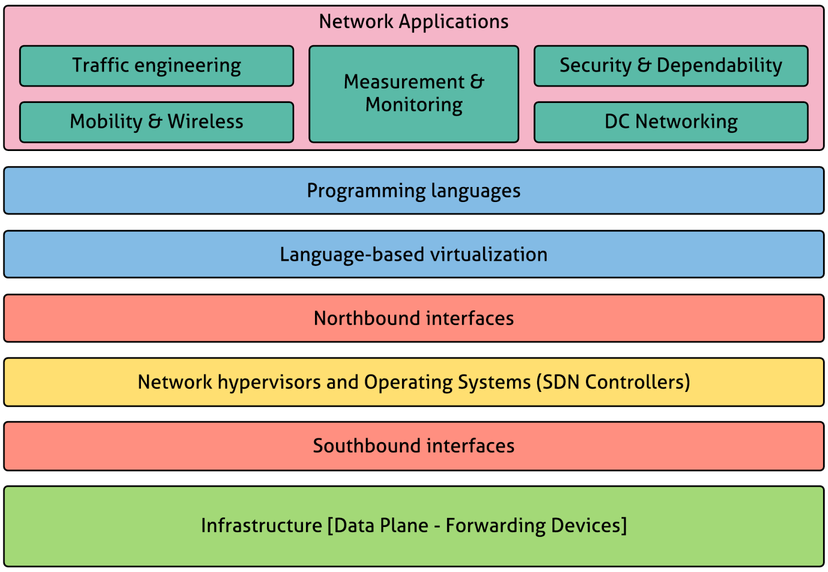

Figure 11: SDN logical research areas classification [KRV+14]

Additionally, authors in [FRZ14] provide a classification of the different SDN approaches also in similar terms and areas. They group the approaches as a function of the architecture (i.e. ForCES or OpenFlow), southbound protocols, forwarding devices, SDN controllers, and northbound interfaces. The network hypervisor, or the SDN controller, is the most representative element related to virtualization, since it is the one responsible for the data plane (infrastructure) abstractions.

The SDN controller has indeed been compared to an operating system [NMN+14], in which the controller provides a programmatic interface to the network. That abstraction, as introduced in Chapter 1, can be used to implement management tasks and to offer new functionalities. A layered, and simplified view, is illustrated in Figure 12. Thus, it enables the SDN model to be applied over a wide range of applications and heterogeneous networking technologies, such as wireless (e.g. 802.11 and 802.16), wired (e.g. Ethernet), and even optical networks.

As a practical example of the layering abstraction accessible through open application programming interfaces we find the Floodlight controller[f] [con]. This particular controller allows the implementation of built-in modules that can communicate with the different OpenFlow services, or either the interaction with the controller through the Representational State Transfer (REST) APIs on the northbound boundary of the system.

In terms of the SDN controller, several concerns arise in terms of future SDN deployments:

- Control scalability. An initial concern that arises when offloading control from the switching hardware is the scalability and performance of network controllers. The original Ethane [CFP+07] controller, hosted on a commodity desktop machine, was tested to handle up to 11.000 new flow requests per second and responded within 1.5 milliseconds. A more recent study [TGG+12] of several OpenFlow controller implementations (NOX-MT, Maestro, Beacon, conducted on a larger emulated network with 100.000 endpoints and up to 256 switches, found that all were able to handle at least 50.000 new flow requests per second in each of the tested scenarios.

The abstraction enables the SDN model to be applied over a wide range of applications and heterogeneous networking technologies

- Control models, or the old, always-emerging questions: centralized or distributed, reactive or proactive policies, and what control granularity is necessary (e.g. per packet or per flow). Traditionally, the basic unit of networking has been the packet. Each packet contains address information necessary for a network switch to make routing decisions. However, most applications send data as a flow of many individual packets. A network that wishes to provide QoS or service guarantees to certain applications may benefit from individual flow-based control. Control can be further abstracted to an aggregated flow-match, rather than individual flows. Flow aggregation may be based on source, destination, application, or any combination thereof. In a software-defined network where network elements are controlled remotely, overhead is caused by traffic between the data plane and control plane. As such, using packet level granularity would incur additional delay as the controller would have to make a decision for each arriving packet. When controlling individual flows, the decision made for the first packet of the flow can be applied to all subsequent packets of that flow.

Research analysis on southbound and northbound interfaces is not included within this chapter, since they are out of the scope of the overall context of the work performed within the dissertation.

f http://www.projectfloodlight.org/

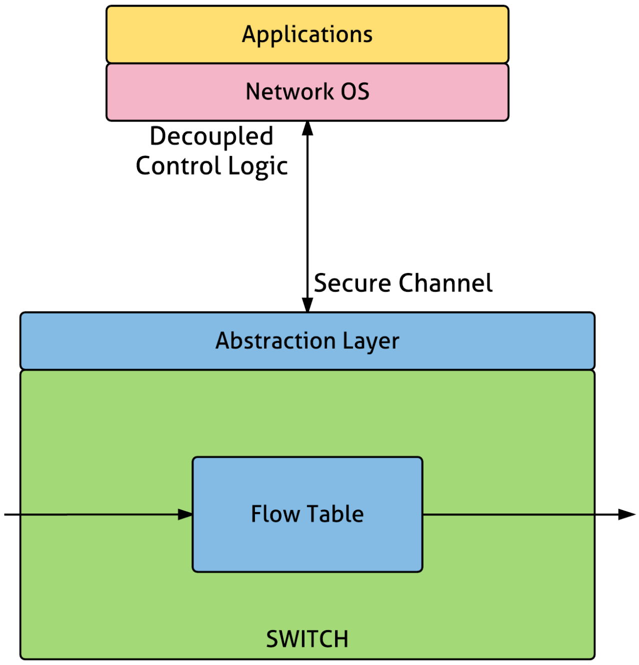

Figure 12: The separated control logic can be viewed as a network operating system, upon which applications can be built to program the network [FRZ14]

2.5.1 *Network Virtualization and SDN*

Although network virtualization has gained momentum as a use case of SDN [NMN+14] or as a complementary technique to enrich SDN [FRZ14], *"the concept predates modern-day SDN"* and has in fact evolved in parallel with programmable networking. In fact, abstraction performed by programmable networking comprehend a key mechanism in order to share the infrastructure resources (across multiple tenants in a DC, administrative groups in the same domain, or experiments over a facility) and to support logical (or virtual) topologies that differ from the physical network, both of which are central tenets of network virtualization. Authors in [NMN+14] also state that *"a precise definition of network virtualization is elusive, and experts naturally disagree as to whether some of the mechanisms (such as partitioning) represent forms of network virtualization"*.

Chapter 1 presents the three cornerstones upon which network virtualization relates to SDN.

- **SDN as an enabling technology for network virtualization**. Cloud computing brought network virtualization to prominence, because cloud providers need a way to allow multiple customers or tenants to share the same network infrastructure. Nicira's Network Virtualization Platform (NVP) [Nic12] offers this abstraction without requiring any support from the underlying hardware. The solution is to use overlay networking in order to provide each tenant with the abstraction of a single switch connecting all of its virtual machines. Yet, in contrast to previous work on overlay networks, each overlay node is a actually an extension of the physical network -a software switch (like Open vSwitch[g] [PPK+09]) that encapsulates traffic destined to virtual machines running on other servers. A logically centralized controller installs the rules in these virtual switches to control how packets are encapsulated, and updates these rules when virtual machines move to new locations.

- **Network virtualization for evaluating and testing SDNs**. The ability to decouple an SDN control application from the underlying data plane makes it possible to test and evaluate SDN control applications in a virtual environment before the application is deployed on an operational network. Mininet [HHJ+12, LHM10] uses process-based virtualization to run multiple virtual OpenFlow switches, end hosts, and SDN controllers -each as a single process on the same physical (or virtual) machine. The use of process-based virtualization allows Mininet to emulate a network with hundreds of hosts and switches on a single machine. In such an environment, a researcher or network operator can develop control logic and easily test it on a full-scale emulation of the production data plane; once the control plane has been evaluated, tested, and debugged, it can then be deployed on the real production network.

- **Virtualizing an SDN**. In conventional networks, virtualizing a router or switch is complicated, because each virtual component needs to run own instance of control-plane software. In contrast, virtualizing a dumb SDN switch is much simpler. The FlowVisor [SGY+10] system enables a campus to support a testbed for networking research on top of the same physical equipment that carries the production traffic. The main idea is to divide traffic flow space into slices, where each slice has a share of network resources and is managed by a different SDN controller. FlowVisor runs as a hypervisor, speaking OpenFlow to each of the SDN controllers and to the underlying switches. Recent work has proposed slicing control of home networks, to allow different third-party service providers (e.g., smart grid operators) to deploy services on the network without having to install their own infrastructure [YYK+11]. More recent work proposes ways to present each slice of a software-defined network with its own logical topology [AS13, DKR13] and address space [AS13].

g http://openvswitch.org

2.5.2 *SDN in the transport domain*

ONF has established a working group in order to apply the SDN principles over the transport networks. Its intention is to guide the development of high-level requirements, architecture, and protocol definition for transport SDN [ONF14]. The initial identified use cases are:

- Direct control of optical components in enterprise networks
- Carrier Ethernet network virtualization
- Service provider data centre interconnection
- Packet-optical integration

Author in [Lan15] ensures that applying SDN in the transport domain will prevent vendor lock-in for the different carrier stakeholders. Typically, when the IP and the optical layers do not share a common control plane, the operator is forced to maintain two disparate systems. A single proprietary system locks the operator into a single vendor, impacting the evolution of the carrier's network, which would be avoided by the deployment of SDN principles in the transport network.

Regarding the question whether is transport SDN just GMPLS repackaged [Ton14], several voices claim that a network is fundamentally multi-domain, multi-layer, and multi-vendor; and precisely SDN provides an open, flexible, and programmable environment that can accommodate diverse and dynamic requirements. Furthermore, the proliferation of huge DCs and cloud computing is bringing new requirements for network-wide policy management, data governance and regulatory considerations, which logically would be handled by SDN control layer and a combination of network applications on top. With GMPLS, there is no straight-forward way handle the requirements- either the network-wide or the changing requirements. GMPLS is not carrier or transport SDN. SDN gives end-to-end network control, service automation, and service agility across this network [Ton14].

Additionally, authors in [CNS13] propose control plane architecture based on OpenFlow for software-defined optical networks suitable for cloud computing services that takes into account the specific requirements. The proposed architecture allows implementation of agile, elastic cloud networks that can adapt to application requirements on demand. The article contains the different extensions required in the OpenFlow protocol to support optical networks. They also evaluate the performance of the proposed architecture through the use of relevant cloud computing use cases, e.g. content delivery.

Furthermore, authors in [CAP+13] proposed and evaluated an optical SDN model, which enables performance comparison of different optical SDN scenarios, as well as network optimization with respect to target parameters (e.g. path provisioning latency). In that model, all that was assumed a priori is a unified control plane with a centralized controller that governs an arbitrary set of software-defined entities, and can establish either vertical or horizontal paths between them, subject to a basic set of rules. The problem was formalized as a linear optimization problem that could be further customized for given scenarios. Latency results presented corroborated and synthesized previous experimental data. In [CTJ+14] the authors proposed the extension of SDN and OpenFlow principles to optical access/aggregation networks for dynamic flex-grid wavelength circuit creation. The first experimental demonstration of an OpenFlow1.0-based flex-grid -flow architecture for dynamic 150Mb/s per-cell 4G Orthogonal Frequency Division Multiple Access (OFDMA) mobile back-haul overlays onto 10GB/s passive optical networks was also detailed.

2.5.3 *SDN in wireless domains*

Undoubtedly, the efforts of the research community to design efficient "last mile" access networks are driven by the growing customer demands for bandwidth-intensive services. To this end wireless back-haul efficiency must be thoroughly investigated, since the adoption of the cloud computing paradigm proved that wireless and wired domains are not uncorrelated as we used to think, in order to provide an ultra fast end to end data path.

A well-known solution to address participation to different networks and implement network isolation is by giving access to the user in a specific wireless network with virtualization techniques such as VLAN or VPN [AE11b].

Other state of the art techniques that can be used to perform network virtualization and isolation of network resources between different entities are SDN solutions with Openflow as a crested or implementations with software routing functionalities.

The OpenFlow specification defines an open protocol to program the flow table in switches and routers. A network administrator can partition traffic into production and research flows. In principle, OpenFlow could be used as a mechanism to separate the production traffic from the experimental traffic, with the former processed as in standard routing, switching equipment. This model/functionality can be used to separate/isolate traffic between different virtualized networks. It has been evaluated in the wired world, like for example Google DCs [KDTR12] but is also adopted as a valuable technique to virtualize wireless back-haul networks [YKS+10]. Other technologies that are very promising but are vendor specific are the Juniper Contrail[h] and the forthcoming Cisco OnePK[i].

Getting into the SDN world where Data, Control Management and Service Planes must be clearly separated, software routers and software switching technologies have also been proposed in the literature to perform network slicing or provide other network functionalities. Such as technology is the Click Modular router[j]. Click routers are built from fine-grained components, named elements, which support and extend the basic functions of the packet forwarding path. Network virtualization ideas that come from operations within the Data centers, could also be evaluated and adopted to virtualize the wireless back-haul network. For example in CloudNaaS [BASS11] the proposed architecture relies on OpenFlow-style forwarding and mitigates the current limited control available to cloud subscribers to configure the network, by providing them access to services like, network isolation, custom addressing, service differentiation, intrusion detection, and caching, see also [SLX12].

Software-defined radios. We also here mention that Genuinely Not Unix (GNU) Radios allow the researcher to program a number of physical layer features (e.g. modulation), thereby allowing for dedicated PHY layer or cross-layer research and is a technique that can be also used to provide virtual wireless networking capabilities. This technology uses Field-Programmable Gate Array (FPGA) technology, and a high-speed set of analog-to-digital and digital-to-analog converters, combined with reconfigurable free software. Useful Information about GNU radio can be found on the official GNU web-site[k] . The Universal Software Radio Peripheral (USRP) products are computer-hosted software radios. USRPs are commonly used with the GNU Radio software suite to create complex software-defined radio systems. USRPs connect to a host computer through a high-speed Universal Service Bus (USB) or Gigabit Ethernet link, which the host-based software uses to control the USRP hardware and transmit/receive data.

2.6 NETWORK FUNCTIONS VIRTUALIZATION

Once SDN established itself as the most promising technology for the novel Internet, including all those changing and dynamic environments, NFV appeared into the arena in order to guide a huge amount of the innovation activities coming from the telecom industry, as described in Chapter 1.

NFV, as defined by ETSI in [NFV14], envisages the implementation of NFs as software-only entities that run over the Network Function

h http://www.juniper.net/us/en/dm/junos-v-contrail/
i http://cisco.com/en/US/prod/iosswrel/onepk.html
j http://www.read.cs.ucla.edu/click/click/
k http://www.gnu.org

Virtualization Infrastructure (NFVI). Figure 13 illustrates the high-level NFV framework. As such, three main working domains are identified in NFV:

- VNF, as the software implementation of a network function which is capable of running over the NFVI
- NFVI, including the diversity of physical resources and how these can be virtualized. NFVI supports the execution of the virtualized network functions.
- NFV Management and Orchestration, which covers the orchestration and lifecycle management of physical and/or software resources that support the infrastructure virtualization, and the lifecycle management of VNFs. NFV Management and Orchestration focuses on all virtualization-specific management tasks necessary in the NFV framework

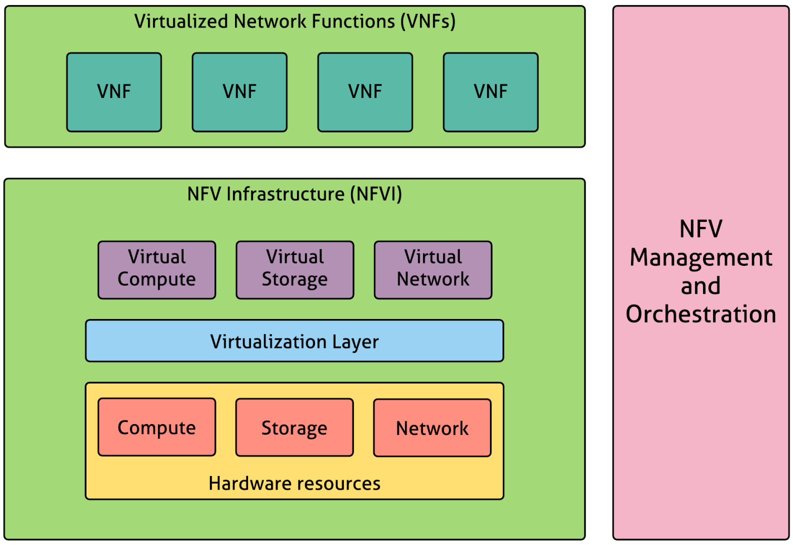

Figure 13: ETSI High-level NFV framework [NFV14]

The NFV framework enables dynamic construction and management of VNF instances and the relationships between them regarding data, control, management, dependencies and other attributes. To this end, there are at least three architectural views of VNFs that are centred around different perspectives and contexts of a VNF. These perspectives include [NFV14]:

- a virtualization deployment/on-boarding perspective where the context can be a Virtual Machine (VM);
- a vendor-developed software package perspective where the context can be several inter-connected VMs and a deployment template that describes their attributes;

- an operator perspective where the context can be the operation and management of a VNF received in the form of a vendor software package.

Within each of the above contexts, at least the following relations between VNFs are derived. First, the need for a forwarding graph, the so called Virtual Network Function Forwarding Graph (VNF-FG), in order to cover and specify the connectivity between the different VNFs; and secondly, the need for a VNF set where the connectivity between VNFs is not specified and resources need to be executed from a pool of available functions at any given instant.

NFV envisages the implementation of NFs as software-only entities that run over the NFVI

In fact, following the ETSI specifications, an end-to-end network service (e.g. mobile voice/data, Internet access, or even a virtual private network) can be described by a Network Function Forwarding Graph (NF-FG) of interconnected NFs and end-points. A network service can be viewed architecturally as a forwarding graph of NFs interconnected by supporting network infrastructure. These network functions can be implemented in a single operator network or interwork between different operator networks. The underlying network function behaviour contributes to the behaviour of the higher-level service. Hence, the network service behaviour is a combination of the behaviour of its functional blocks. Figure 14 depicts the representation of an end-to-end network service within the NFV environment.

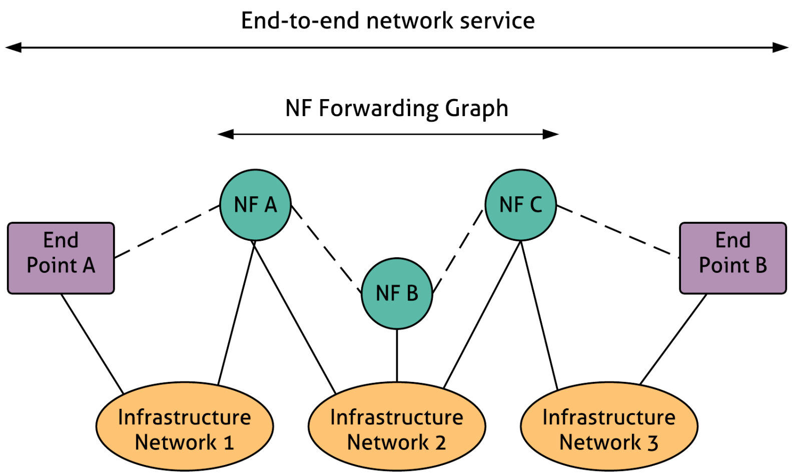

Figure 14: Graph representation of an end-to-end network service [NFV14]

In this example, an end-to-end network service can be composed of only VNFs and two end points. The decoupling of hardware and software in network functions virtualization is realized by a virtualization layer. This layer abstracts hardware resources of the NFV Infrastructure. NFV emphasizes the fact that the exact physical deployment of a VNF instance on the infrastructure is not visible from the end-to-end service perspective.

Therefore, ETSI NFV defines network services as entities composed of virtual network functions, which are the actual components performing the specific operations [NFV14]. Typically, network traffic associated to a given Network Service (NS) goes through several network functions. As authors state in [MKK14] that means a set of network functions is specified and the flows traverse these functions in a specific order so that the required functions are applied. This implies precedence requirements between functions in the same service, which is known as the formalization of the function chaining. In this regard, performance of network services will be affected by both the different composing functions' behavior and the order in which functions are processed.

In essence, NFV adds new capabilities to communication networks, but it requires a set of management and orchestration functions to be added at the current model of operations, administration, maintenance, and provisioning in order to meet the expected challenges and fulfill the carrier-grade requirements [NFV12b]. The virtualization insulates the network functions from the infrastructure resources, where they run both networking and computing through a common virtualization layer. This decoupling opens the door to the exposure of a new set of entities, adding new relationships between them and the NFVI where they are allocated and scheduled.

As a summary, the generic end-to-end network service model and its realization through virtualization (and its provisioning on actual infrastructures) techniques requires additional functionalities, such as mapping and scheduling of virtual network functions, which are considered part of the management and orchestration framework. Thus, ETSI published the NFV architectural framework [NFV14], which addressed the following:

- The functionality that is required to be realized by the NFVI.
- The functionality that is required due to decoupling network functions into software and hardware.
- The functionality that is required for NFV-specific management and orchestration.

It is worth to mention at this stage that the required end-to-end network service and the delivered behaviour shall be equivalent among virtualized and non- virtualized scenarios. Figure 15 depicts the overall architecture for the ETSI NFV framework. On the right part of the image it is depicted the management and orchestration component, considered as the fundamental cornerstone for the NFV. The management and orchestration layer within the NFV stack is responsible for the deployment and operation of the different network services. For a complete description of the different functional components on the NFV architectural framework please refer to [NFV14, NFV12a].

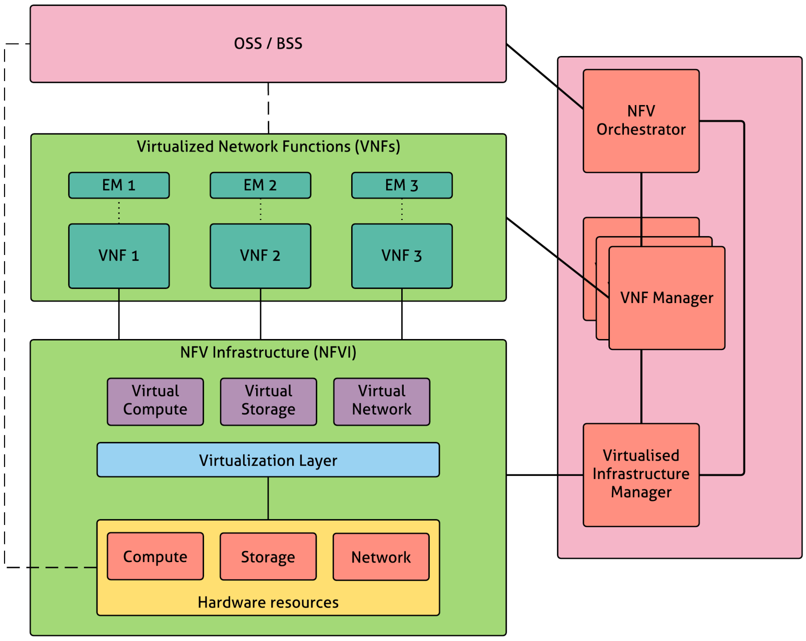

Figure 15: ETSI NFV architectural framework [NFV14]

In detail, the NFV orchestrator is in charge of the orchestration and management of the NFVI and software resources, as well as the realization of the different network services on the NFVI. The service model will contain deployment templates, descriptors, the forwarding graph, and the different infrastructure information models. The NFV Management and Orchestration functional blocks will handle all this information in order to complete the service provisioning (within the NS and VNF lifecycle management.

Therefore, the first challenge to the deployment of those services composed of virtual network functions becomes the composition process of the NS itself [MKK14], i.e., how the virtual network functions are chained together to compose a NS, while still considering the possible dependencies, precedence, and connections between them. Service providers will need to face such a challenge to deploy customized and dynamic NFV-enabled network services. It nearly becomes obvious that the second challenge can be identified as the embedding process, i.e., where in the NFVI infrastructure the virtual network functions will be allocated. Different servers in the NFVI will have different processing capabilities, or different hardware characteristics, which will affect the service performance. While this is true for all the virtual network functions processing traffic continuously, e.g., Deep Packet Inspection (DPI), there are other specific functions which are only executed during a certain time period, e.g., virtual Path Computation Element (PCE), which is a fundamental building block for traffic engineering systems as Multi-Protocol Label Switching (MPLS) and GMPLS [FVA06], or multi-domain virtual forwarding function, as presented in [BFREGE13], which computes the path between two independent administrative OpenFlow-enabled networking domains. A new challenge comes into the arena for the last group of virtual network functions, the scheduling, i.e., when is it better to execute each function in order to minimize the total execution time without degrading the service performance and respecting all the precedence's and dependencies between the functions composing the service at the same time.

More details on each challenge and the current solutions or approaches to each one of them are discussed later on Chapter 9.

Finally, it is worth to mention the different standardization activities taking place over the NFV concept in order to finalize with the overview: Those standardization activities run in parallel the ETSI NFV, which was the first institution to launch the concept and to coin the name.

IETF Service Function Chaining Group. Functions in a given service have strict chaining and/or ordering requirements that must be considered when decisions to place them in the cloud are made. The Internet Engineering Task Force (IETF) [For15]has created the Service Function Chaining Working Group (SFC-WG) [Cha15] to work on function chaining. The IETF SFC-WG is aimed at producing an architecture for service function chaining that includes the necessary protocols or protocol extensions to convey the service function chain and service function path information to nodes that are involved in the implementation of service functions and Service Function Chains (SFCs), as well as mechanisms for steering traffic through service functions.

IRTF NFV Research Group. The Internet Research Task Force (IRTF) has created a research group, Network Function Virtualization Research Group (NFVRG) [Vir15], to promote research on NFV. The group is aimed at organizing meetings and workshops at premier conferences and inviting special issues in well-known publications. The group focuses on research problems associated with NFV-related topics and on bringing a research community together that can jointly address them, concentrating on problems that relate not just to networking but also to computing and storage aspects in such environments.

ATIS NFV Forum. The Alliance for Telecommunications Industry Solutions (ATIS) NFV Forum [fTIS15] is an industry group created by the ATIS, a North American telecom standards group. The group is aimed at developing specifications for NFV, focusing on aspects of NFV which include inter-carrier interoperability and new service descriptions and automated processes. ATIS NFV Forum plans to develop technical requirements, the catalog of needed capabilities and the service chaining necessary for a third party service provider or enterprise to integrate the functions into a business application. This process is expected to result in creation of specifications

2.7 TIMELINE AND CONTEXT

In order to complete the introduction and related work analysis, it becomes fundamental that we provide a timeline of the different virtualization-related topics considered relevant for the work within the dissertation. Figure 16 provides such an overview accordingly adapted to the time when things emerged and happened.

The map only aims at providing a contextual schema of the timeline of the different relevant topics. For specific dates, the reader is referred to the corresponding bibliography already presented. Following the same structure as the one up to the moment, the figure includes the following topics as relevant:

- DC virtualization
- Service oriented architectures
- Network Virtualization
- Network + IT virtualization
- Cloud computing
- Wired / Wired convergence
- Software-defined networking
- Network functions virtualization

Moreover, Figure 17 presents a detailed, logical mind-map of the related work presented within this chapter of the dissertation. Additionally, in order to complete the contextualization of the dissertation activities, Appendix A provides an overview of the different international research projects within most of the activities where carried.

It is worth to mention at this stage that the projects themselves do not represent the dissertation. The projects apply the virtualization concept over different entities (e.g. resources, technologies, functions, etc.). They are huge international collaborations and represent a proof of the time soundness of the activities carried out in parallel for the doctoral thesis, i.e. the virtualization leitmotiv behind them (and the thesis) provides an added-value bridging the bilateral exchange of information between the projects in the environment and the activities summarized in this document.

There is the necessity to include the summary of the projects in the appendix A in order to enable the reader with a complete understanding of both the contributions and proposals made during the PhD journey, which are later described in the following parts of the document.

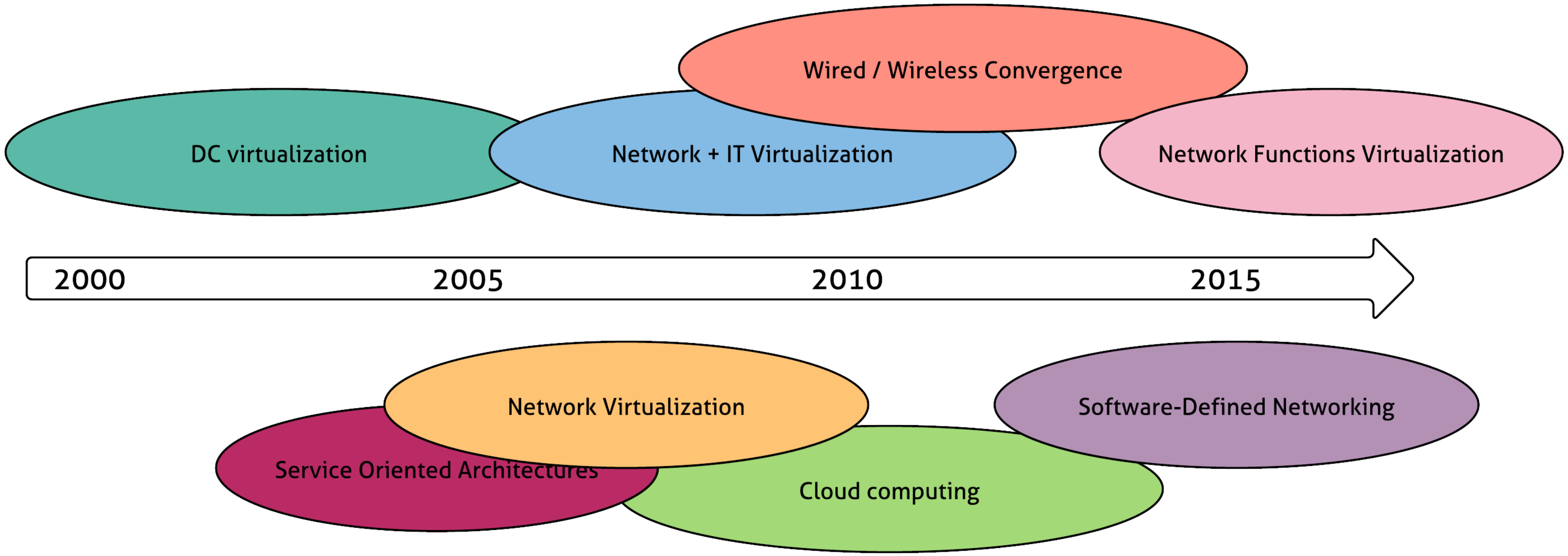

Figure 16: Overall timeline of the virtualization-related topics considered within the dissertation

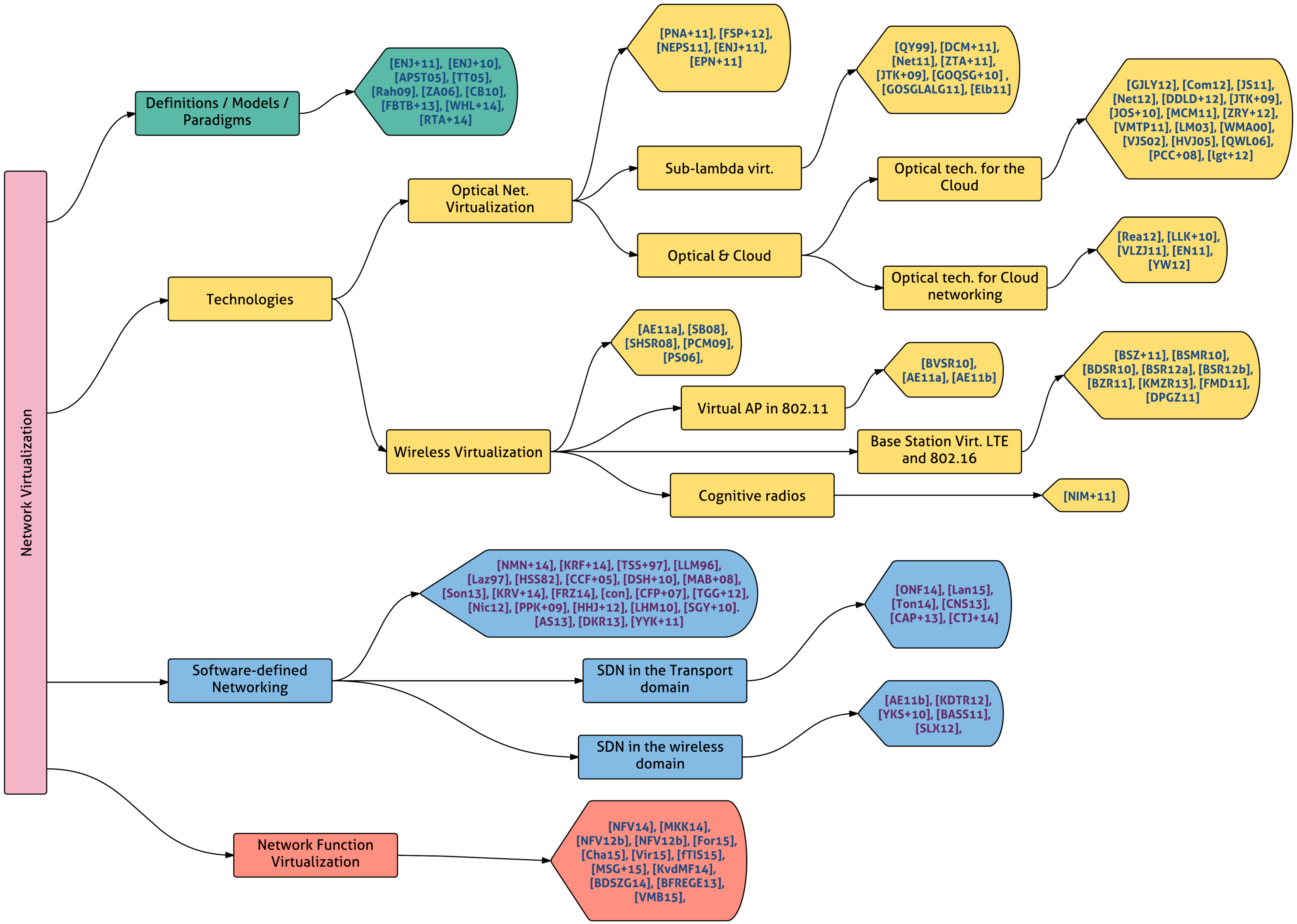

Figure 17: Mind-map of the related work

3 PROBLEM DESCRIPTION, MOTIVATION, AND CONTRIBUTIONS

Ash nazg durbatulûk, ash nazg gimbatul,
ash nazg thrakatulûk agh burzum-ishi krimpatul.
- (Inscription upon the One Ring)

Author in [Cre07] states that *"research is a process of making discoveries: these may be new empirical regularities, new theoretical insights and an improved understanding of economic problems. This presents a difficult challenge. Contrary to a popular illusion, such progress is largely achieved by making a series of small steps, rather than taking giant leaps. The clear specification of the problem is an important element in planning a project. The question has to be clearly defined and seen to be worthy of attention. Eventually, you should be able to state clearly what you have contributed to knowledge"*.

He follows *"the understandable tendency to look at the final destination instead of the closer road ahead is reflected in the first question often asked by PhD students. They want to know what is expected of them — what do they have to do to get their PhD? The standard answer is of course that a PhD is normally described as containing material for three publishable papers. This response is nevertheless both vague and an oversimplification. The thesis should have a central core or theme which ties the separate contributions together, although the closeness between topics differs significantly among theses"*.

Considering the environment, and the overall related work presented up to the moment, it is nearly explicit that the core topic of the dissertation is virtualization. The question, however, is *Virtualization of what?*. First and most rapid answer becomes thus network virtualization. Again, a quick overview to Chapters 1 and 2 (as well as Appendix A) triggers more detailed question about *What type of network virtualization?*; or even *What type of network technologies are considered for virtualization?*. While there are hundreds of different approaches to network virtualization, including different resources, services, or even technologies, the key question to determine in network virtualization environments can be summarized as *Where to allocate the virtual resources?*, i.e. which physical resources will be utilized in order to host the virtual resources that will be created within a given virtual infrastructures?.

Basically, in plain words, this is the virtual embedding or allocation problem. For example, consider that there is an underlying physical infrastructure composed of different resources. There is one owner for these resources. Let us assume that this infrastructure can be abstracted and manipulated. The manipulation process is characterized by the corresponding resources' characteristics. Moreover, consider that there is one business role, apart from the owner of the infrastructure, who is granted to access the physical substrate and to abstract and manipulate it in an on-demand fashion. So that this new role holds the capability of building virtual infrastructures composed of different manipulated resources offering them as a service towards third-party stakeholders, which can later on operate those virtual infrastructures. Figure 18 depicts the allocation problem described here.

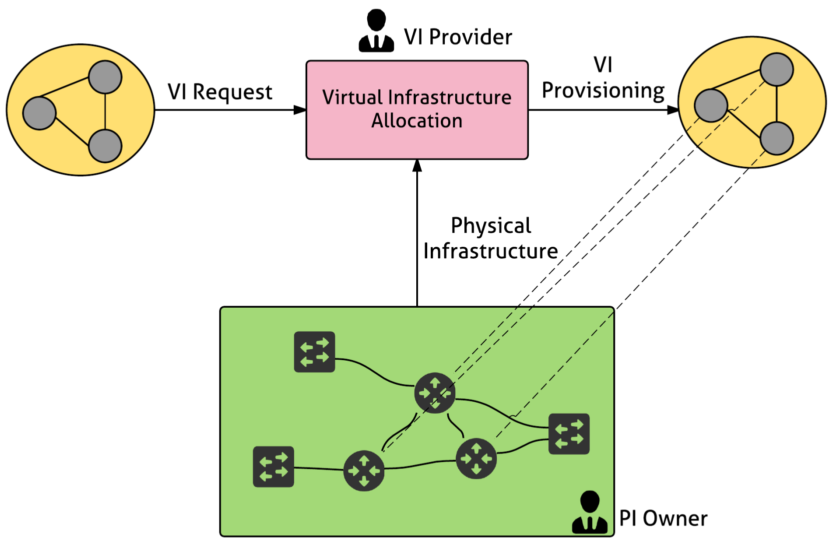

Figure 18: Virtual Infrastructure allocation or embedding problem: schematic overview

Several open questions appear within this apparently simple scenario that are (some of them were) to be solved. First of all, the information model to represent the whole environment, both the physical and virtual levels, acquires importance, since it is the element on which the whole problem will be modelled and addressed. Secondly, we have the information exchange mechanisms between the different roles involved in the provisioning process. Last but not least, which virtualization mechanism and process is to be followed in order to abstract, select, and manipulate (partition, aggregate, etc.) the corresponding resources which will be utilized to compose the different VIs. The problem could be stated as follows:

> *On the one hand, we have to determine whether the requests can be satisfied with the set of available physical resources present in the Physical Infrastructure (PI) or not. On the other hand, and assuming the case that all the resource requests can be satisfied, we have to determine how these requests are satisfied; meaning this that the virtualization mechanism has to define the manner in which the VIs are composed and built. This process includes what resources are to be selected, and how the different resources are partitioned and allocated among the different virtual infrastructures.*

Basically, one could argument that the problem has been in the literature since the emergence of network virtualization [CB10]; even before, considering other realms, such as IT systems virtualization, for instance. Within such a problem, the next direct question emerging over this allocation or embedding problem is how the virtualization is materialized, i.e. which resources are selected and why. Figure 18 does not indicate any extra input into the *virtualization black-box system* in order to guide the allocation process (i.e. why to select one resources or the others). Typically, in a mathematical formulation of the problem that would comprehend the objective function. For example, *the system selects physical resource* a *to build virtual resource* b *because it minimizes the economical cost*.

We have to determine whether the requests can be satisfied with the set of available physical resources present in the PI or not

In a high-level representation of the problem, such objective function could be considered as a policy. Therefore, the virtualization black-box system receives an additional input, the policy upon which the virtual infrastructures will be materialized. We define the system as a policy-based system to compose virtual infrastructures.

In fact, policy-based systems are present in several research areas due to its dynamism and modularity. Since the beginning of the 1990s the policy paradigm has been proposed to be applied in the area of network management [RKS02]. The first major application of policies was access control in distributed systems, often termed *role-based access control* [SCFY96]. A broader application of policies in the Internet was in QoS management, mainly in addressing the Integrated Servicess (IntServs) and Differentiated Services (DiffServs) architectures. The IETF Internet Protocol (IP) security policy working group worked on communication security policies mainly for Internet Protocol Security (IPSec) architecture. The use of policies for network management has different advantages over, for example, manual (i.e. command line) configuration or management via Simple Network Management Protocol (SNMP). The separation of a policy from an implementation enables dynamic changes to the management of systems and modification of the behaviour of the system. And these are only the most known policy-based system applications. The reader can find more examples in [ABB+03], [ACGL04], [ZGLC03], or [BSE+07] among others.

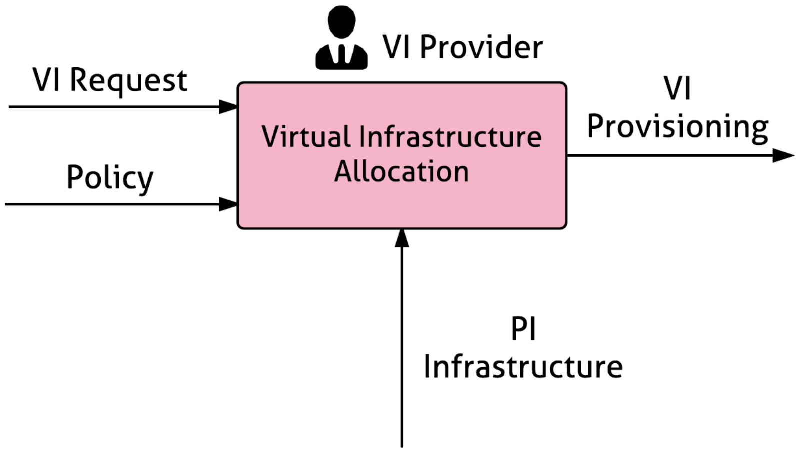

Figure 19: Policy-based virtual infrastructure allocation system

we have to determine how these requests are satisfied; meaning this that the virtualization mechanism has to define the manner in which the VIs are composed and built

Defining policies in the system enables the provider to dynamically adapt the virtualization process to the given requirements. As policies can be dynamically changed, the virtual infrastructure provider may use the system with different previously defined policies at any time. Moreover, policies can be combined in order to create complex policies that better optimize a given parameter or set of parameters. Dynamicity and flexibility of a policy based system allows that our virtual infrastructure provisioning system, seen as a black box, may be used by a complete set of provider aiming at using totally different policies.

A clear example of a given policy would be to provision virtual infrastructures trying to minimize the total amount of energy consumed by the selected physical resources to be virtualized in order to compose the VI. Furthermore, consider also another policy that would consist of minimizing the total amount of power consumed and also in minimizing the CO_2 emissions by means of using the maximum number of Physical Resources (PRs) connected to a *clean* source of energy (e.g. eolic energy source). Furthermore again, consider the previous policy. One provider can extend it and create a more complex one by means of adding to it the prioritization of using resources that are geolocalized in countries that are compliant with agreements signed in the Kyoto protocol[a].

a The Kyoto Protocol is an international agreement linked to the United Nations Framework Convention on Climate Change. The major feature of the Kyoto Protocol is that it sets binding targets for 37 industrialized countries and the European community for reducing greenhouse gas (GHG) emissions. These amount to an aver-

The flexibility of the policies is that each provider may define its own policy and actuate according to it. Another simple policy example is the economical cost associated to each resource. Consider that vitalizing a given PR holds an economical cost to be paid. Thus, a simple policy may be minimizing the economical cost of the virtual infrastructures by means of minimizing the cost of the involved resources.

policies can be combined in order to create complex policies that better optimize a given parameter or set of parameters

Once the problem is clear, the activities in the dissertation could be started working around this problem, focusing on the policy-based virtualization over optical networks, including IT requirements coming from the Cloud computing paradigm. Several contributions to the community were made over this topic, as it is summarized in Section 3.2 and extended in Chapters 4, 5, 6, and 7.

However, at some stage during the initial contributions, it was identified that static planning algorithms or approaches were a waste of resources for dynamic environments such as Cloud computing. In big DCs, hundreds of VM change its state every hour, as a function of the dynamic, and constantly evolving requirements of the cloud-based applications and services, highly coupled to the virtual infrastructures operation. Some of those changes could be predicted, e.g. a web-based distributed enterprise information system which is utilized during working hours, and infra-utilized during nightly hours; and some others directly cannot be predicted due to its nature.

Considering these variables and requirements, the first step towards the completion of the dissertation around the network virtualization topic came with the dynamic re-planning of virtual infrastructures in order to coordinate networking resources and cloud services, so the waste of networking resources is minimized. This proposal, combined with all the contributions at the virtual infrastructure planning problem, represent the first *small step* towards the end of the PhD journey. Details on this dynamic re-planning proposal are provided later in Chapter 8.

Finally, at the latter stages of the work, SDN and NFV emerged into the arena as the most promising concepts towards a completely novel manner in terms of network management. Basically, network virtualization could be considered as a way to manage networks; and thus, NFV was the natural evolution of the thesis activities. Virtualization can be indistinctly applied to IT servers, network resources, and even network functions.

There is an specific challenge for virtual network functions, which is completely different from the infrastructure virtualization itself

In essence, there is no difference in virtualizing resources or network functions; at least, in terms of the allocation or embedding

age of five per cent against 1990 levels over the five-year period 2008-2012. The major distinction between the Protocol and the Convention is that while the Convention encouraged industrialized countries to stabilize GHG emissions, the Protocol commits them to do so. More info can be found at United Nations Framework Convention on Climate Change public web site http://unfccc.int/kyoto_protocol/items/2830.php problem. You need to decide over which virtual resources (standard high-volume servers for NFV will the virtualized network functions be deployed. Obviously, the constraints and requirements of the virtualization process (i.e. embedding) will be different, since characteristics of network resources and network functions are not equivalent. For example, one can consider that the forwarding graphs representing network services within the NFV realm hold precedence requirements (i.e. function a cannot be executed before function b), which typically is not the case for virtual infrastructures, although there are some cases of unidirectional links also considered in the literature.

However, there is an specific challenge for virtual network functions, which is completely different from the infrastructure virtualization itself. There are some specific functions which represent control functions, rather than data plane functions. Thus, they do not deal with the traffic itself, but only take decisions which affect the traffic. When virtualizing these functions, they only need to be executed during a given time slot, then the IT server could be released to host and execute another function.

This problem was identified as the other cornerstone of the thesis activities, and we proposed virtual network function scheduling as one emerging problem to be analyzed and studied. Chapter 9 provides details on the problem itself and the initial solution we provided. Scheduling of virtual network functions is still a non-closed research activity, and there is a lot to learn from high performance computing scheduling and operating systems scheduling, where a huge amount of research has been produced around the scheduling topic.

3.1 DISSERTATION OBJECTIVES

I have been always said that a PhD thesis is a journey with three well-known phases or stages, which cannot be skipped nor repeated. The stages can be identified as follows, as well as they have been introduced in the Preface:

- Initial immersion and analysis of the research community around a research topic
- Contributions and collaborations to the topic, improving the own research capabilities and acquiring a deep understanding of the topic and existing problems within it.
- Proposing a novel approach over the topic in order to provide a solution for some of those problems, which still have not been solved.

Considering this structure, the current manuscript has been written following such stages. Thus, the first part presents the environment analysis, and the history in the last years for all the topics around virtualization of resources (both IT and network - wired and wireless). The second part of the dissertation contains the initial contributions provided around the virtualization topic, focusing on optical networks and different characteristics of those resources. Finally, the last part of the work comprehends the novel proposals completed. Figure 20 depicts the timeline of these stages.

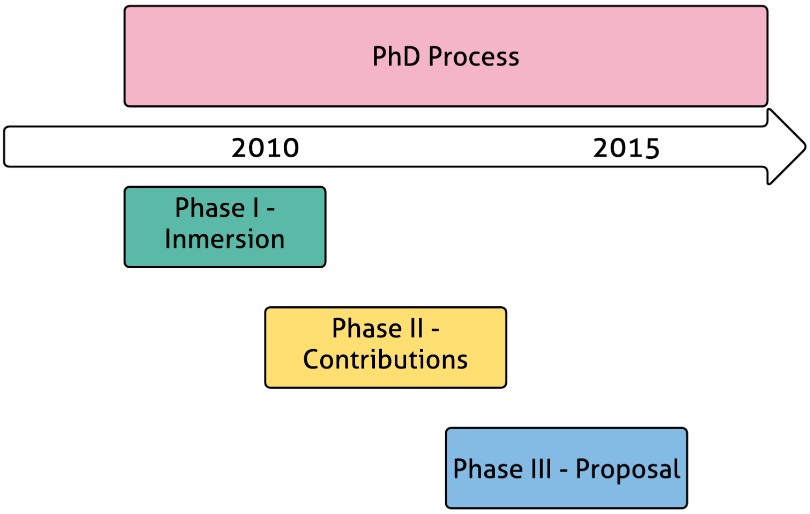

Figure 20: Overall timeline of the dissertation activities

As for the generic objectives of the dissertation, they can be summarized as the successful completion of the three aforementioned stages. Basically the generic objectives can be summarized as: (i) initial state of the art analysis of the network virtualization environment and missing allocation problem parts; (ii) initial contributions to the virtual infrastructure allocation problem, improving current solutions available in the community either in terms of problem approach, improved solutions, or novel metrics; and (iii) proposal of a new solution within the virtual infrastructure allocation problem, coordinated with IT resources.

Within these generic objectives, tightly coupled to the PhD general phases or stages, there exists the need to define specific objectives which must be addressed during the dissertation. Those specific objectives identified for the successful accomplishment of the doctoral thesis are detailed in the next sub-section 3.1.1.

3.1.1 *Specific objectives*

Initially, a set of specific objectives were defined within each stage of the thesis. They are listed in the following bullet points, grouped by the generic objective which contains them.

- State of the art (macro-objective I)
  1. Overall virtualization analysis, both IT and network
  2. Generic optical networks and cloud computing analysis
  3. Detailed network virtualization problem analysis, for both wired and wireless resources
  4. Network virtualization environment considerations and identification of existing solutions, including novel technologies such as SDN
  5. Analysis of the novel trends for virtualization, i.e. NFV and associated standardization efforts
  6. Definition of the virtual infrastructure service provisioning problem and its components (e.g. requests or demands, physical infrastructure, policies)
- Contributions to the virtual infrastructure service provisioning (macro-objective II)
  1. Analysis of the physical infrastructure impact in the virtual service provisioning problem
  2. Analysis of the pre-processing requests in the problem
  3. Contribution at the metrics to be analyzed under heterogeneous physical infrastructure
- Novel proposals to the virtual infrastructure service provisioning (macro-objective III)

Figure 21 depicts the natural flow of the macro-objectives, and how the completion of one followed the starting of the next macro-objectives. The successful accomplishment of the objectives' chain, tightly related to the phases as depicted in Figure 20, comprehends the successful accomplishment of the doctoral challenges.

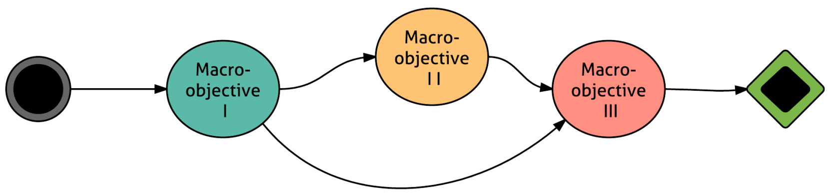

Figure 21: Doctoral thesis objectives' chain

For the last macro-objective, at the beginning of the dissertation activities, there was no specific objective, as it was difficult to envisage the final proposal of the thesis. Instead, during the completion of the first and second macro-objectives, it was naturally derived the two major proposals created during the last stage of the doctoral thesis:

- Dynamic re-planning of virtual infrastructures
- Virtual network function scheduling problem definition, formulation, and initial heuristic solution

Figure 22 summarizes both the macro- and the specific objectives as previously described.

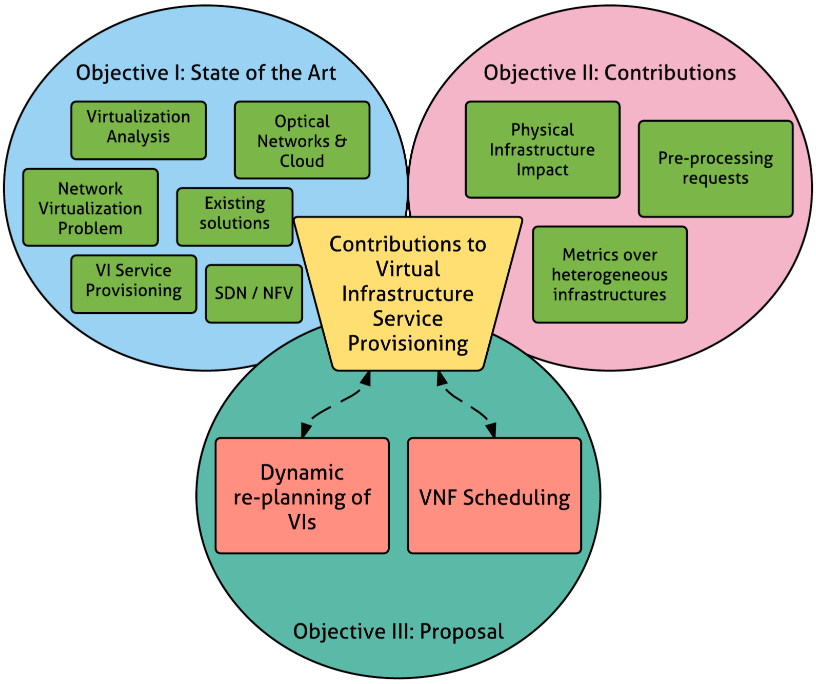

Figure 22: Graphical summary of the dissertation objectives

3.2 DISSERTATION CONTRIBUTIONS

This section describes the major contributions of the dissertation activities, marked within the aforementioned objectives (refer to Section 3.1. The major contributions are summarized in the following bullet points. For each one of them, later on described in the different chapters, the contributions by the author of the dissertation to the collaborative work with the rest of the co-authors are summarized. The publications produced by each one of the collaborations are also detailed in this section.

- Contribution at the virtual infrastructure allocation or embedding problem, focusing on optical networks. The summary of the contributions and the knowledge acquired during the first and second stages of the dissertation derived the co-authorship of several virtualization-related articles, which are not only related to one single contribution. The most relevant are [BMA+14], [FGGE+13], [VBFC+11], [SRGE+11], [FGERC10], [WFRGE+10], [EPN+11], and [GERFL12].

1. Virtual optical network allocation depending on the substrate (fixed or flexible) - refer to Chapter 4. This contribution focused on the analysis of the physical substrate in the virtual infrastructure service provisioning workflow. There was an ILP formulation of the problem for two different optical substrates, and the analysis of the resolution of the exact formulations considering the number of virtual infrastructures created. The collaboration between all the co-authors produced [PPS+12].

2. Clustering of virtual infrastructure requests - refer to Chapter 5. The contribution here was based on previous analytic and formulation work by some co-authors. The work was focused on analyzing the impact of clustering the requests while relaxing the isolation constraint. The part of the control plane analysis and scalability is not part of the author's work. The collaboration produced [RGEF+12], and [GERF+12].

3. Minimizing energy consumption in converged IT + Net virtual infrastructures - refer to Chapter 6. The analysis of different metrics started with the energy consumption. The collaboration by the co-authors here was focused on minimizing the energy consumption of the underlying optical network, coupled with IT resources. This collaboration partially produced the following publications [TAG+11b], [TAG+11a], and [TAG+12].

4. Optical wireless network convergence in support of mobile cloud services - refer to Chapter 7. This contribution continued focusing on the energy minimization while provisioning virtual infrastructures, as the major contribution of the author to the collaborative work. However, the differentiation here is that the substrate considered was both wireless and wired. Delay considerations and mobile offloading were included in the approach as part of the work of the co-authors, but not as direct part of the dissertation activities. The collaboration produced the following publications [ATR+15], [ATZ+13], [KKL+13], [TAL+14], [TAP+14], and [FRBE+14].

- Proposal of dynamic re-planning of virtual infrastructures enabling converged optical networks and DCs - refer to Chapter 8. This comprehends the first proposal of the dissertation. It was focused on the dynamic re-planning of the virtual infrastructure provisioning service, since it becomes key component for the coordination of cloud and optical network resource in an optimal way. The proposal results have been published in [RTA+14], [TAG+14], and [FREB+13].

- Definition of the virtual network function scheduling problem, concept, and challenges; and initial solution to the virtual network function scheduling problem - refer to Chapter 9. This is the second major contribution of the thesis, since the scheduling problem was defined for the NFV realm, and a initial solution proposed utilizing a heuristic. The work here produced the following publications [FRHE+14], [FREB+14], and [FRHZ+15].

Part II

CONTRIBUTIONS

Y yo no he muerto.
Me alegro de la lluvia y me alegro del viento.
Si tengo frío me caliento.
Si tengo miedo, que no lo tengo,
susurro y pienso. Y para mañana
ya me he comido mi pequeña ración de esperanza. Una sola puerta de tres, abierta.
Una sola puerta, inmensa.
- MANOLILLO CHINATO (Amor, Rebeldía, Libertad y Sangre)

PREFACE

The second stage of the doctoral thesis becomes critical for the whole process, since it represents the stage where the research topic is matured enough to get into the last stage. The core objective of this stage is to use the environment analyzed during the first phase and to provide initial contributions at the research community within the given topic.

This part presents the different contributions performed around and within the converged virtualization problem, focusing on the virtual infrastructure provisioning problem, where before instantiating the new virtual resources on top of the actual physical ones, the allocation decision needs to be completed; i.e. where to host the different virtual resources composing each virtual infrastructure.

This part describes different approaches to the generic virtual infrastructure provisioning problem. The contributions addressed within this chapter comprehend the first ports visited during the journey.

The first contribution addresses the analysis of the substrate in order to maximize the number of virtual infrastructures or virtual optical networks in this specific case which could be deployed on top of such physical substrate. The analysis considers two different technologies in the substrate, fixed and flexible grid scenario. Basically, the idea is to analyze the impact of different physical infrastructures at the moment of provisioning the virtual infrastructures.

Taking a look at the other input components of the problem defined in Chapter 3 (i.e. physical substrate, policy, and VI requests), the next logical step is to analyze what would happen in the case that VI requests are processed on beforehand. In detail, the next contribution in the area relaxes the isolation constraint between virtual infrastructures and analyzes the effects on clustering those requests, including the constraints on the scalability of the control plane which will be controlling the provisioned VIs.

Following, the next contribution goes back to the analysis of the policies introduced in the virtualization problem. Basically, we utilize the same architectural background as in the first approach in order to minimize the energy consumption at the moment of provisioning a VI, considering optical network technology within the physical substrate. IT resources are also considered in the problem, since they are responsible for cloud-enabled services.

Finally, the last contribution introduces into the virtualization problem the network convergence topic. In essence, the problem addresses the convergence of LTE access networks together with the optical metro network, following the architectural approach extracted from the project referred in A. This last contribution is one of the firsts in the community to introduce the network convergence (i.e. cross-domain virtualization) into consideration.

4 OPTIMAL ALLOCATION OF VIS DEPENDING ON THE SUBSTRATE

Hige sceal þē heardra, heorte þē cēnre,
mōd sceal þē māre, þē ūre mægen lytlað.
- The battle of Maidon

Typically, different transport technologies may impact on both the amount and the characteristics of the different virtual infrastructures that can be built on top of a given physical infrastructure. In order to analyze the impact of the transport technology, in this contribution (refer to [PPS+12]) two exact ILP formulations that address the off-line problem to optimally allocate a set of virtual infrastructures on top of two different substrates are presented: wavelength switching or spectrum switching. The work presented within this contribution, including formulations, and experiment executions, is a collaboration with the different co-authors in [PPS+12].

Two alternatives enabling optical transport technologies have been considered as cases of study

Basically, two alternatives enabling optical transport technologies have been considered as cases of study in order to determine the impact of the underlying optical network substrate technology on the number of virtual infrastructures that can be allocated by means of the Logical Infrastructure Composition Layer (LICL) planning system[a]: (i) wavelength switching following the fixed-size spectrum grid defined by the International Telecommunication Union (ITU)[b], where the minimum granularity to allocate a virtual infrastructure is a full wavelength [Itu02]; and (ii) spectrum switching, following a flexible spectrum grid as proposed in the Spectrum-slice Elastic Optical Path Network (SLICE) architecture [JTK+09]. In such a case, demands request a portion of spectrum, equivalent to a number of Frequency Slots (FSs) that can be efficiently allocated and switched thanks to the use of optical OFDM and Bandwidth Variable Wavelength Cross Connects (BV-WXC) [Arm09, AMZ+11, AIZ+11].

In both scenarios it is assumed that opaque transport services are being provisioned from the VONs point of view, that is, assuming that

a For details on the LICL architectural component, and the role of such an intermediate layer in service-oriented architectures the reader is referred to Appendix A. The LICL is one of the components defined within the GEYSERS architecture

b http://www.itu.int

every node in the VON has electronic termination capabilities (e.g., is equipped with IP routers). Moreover, it is assumed an all-optical network substrate without wavelength / spectrum conversion capabilities, so that every virtual link of the VON must ensure the wavelength / spectrum continuity constraint. Note, however, that thanks to the Optical - Electrical - Optical (OEO) conversion stages, such a wavelength/spectrum continuity constraint can be relaxed among the virtual links composing the VON. Lastly, it shall be pointed out that the effects of the Physical Layer Impairments (PLIs) introduced in the optical network substrate were not considered in this work to assess the feasibility of the provisioned virtual links. Provided that the proposed models would have to be applied to very large network scenarios, where the PLI could be a concern, the set of candidate paths connecting VON neighbouring nodes should have to be restricted, including only those paths whose physical distance would enable the desired bit-rate.

4.1 PROBLEM FORMULATION

Let the optical network substrate be characterized by a graph $G = (N, E)$, where N denotes the set of nodes and $E = \{(i, j), (j, i) : i, j \in N, i \neq j\}$ the set of physical links. Consider D as the set of demands of virtual infrastructures to be allocated. Each demand $d \in D$, is characterized by a graph $G'_d = (N'_d, E'_d)$, $N'_d \subseteq N$, $E'_d = \{(i, j), (j, i) : i, j \in N'_d, i \neq j\}$. The allocation problem consists of accommodating all or the maximum number of virtual optical networks from the demand set, given the limited capacity of the underlying optical network. VONs are treated as entities instead of a composition of lightpaths, which makes the problem differ from classical route and assignment problems with the objective to maximize the number of lightpaths established. Indeed, a specific demand $d \in D$ is considered to be accommodated only in the case that all its virtual links E'_d can be mapped or allocated over available resources. In case there is any virtual link not mapped or allocated, the demand is considered as not accommodated, and thus it is counts for the blocking probability analysis.

There are two ILP formulations, one corresponding to each scenario: the fixed-size grid and the flexible-grid architecture.

4.1.1 *Fixed Allocation*

We denote W as the set of available wavelengths per physical links and W_d the number of wavelengths desired per virtual link by the demand $d \in D$. We define P as the set of paths in the physical network, $P_{\{e',e\}}$ as the set of $p \in P$ associated with virtual link e' that traverse edge $e \in E$, and $P_{\{e',d\}}$ as the set of $p \in P$ associated with virtual

link e' in demand d. The problem variables for the fixed allocation are: $x(d, e', p, w) = \{1$ if for demand d the virtual link e' is supported through path p and wavelength w, 0 otherwise$\}$;
$y(d, e', p) = \{1$ if in demand d all the wavelengths requested by virtual link e' use the same path p, 0 otherwise$\}$;
$z(d) = \{1$ if demand d can be satisfied, 0 otherwise$\}$.
The ILP formulation is stated below:

$$\max \sum_{d \in D} \alpha_d z(d), \text{s.t.} \tag{1}$$

$$\sum_{d \in D} \sum_{e' \in E'_d} \sum_{p \in P_{\{e',e\}}} x(d, e', p, w) \leqslant 1, \forall e \in E, w \in W \tag{2}$$

$$\sum_{p \in P_{\{e',d\}}} \sum_{w \in W} x(d, e', p, w) \leqslant W_d, \forall d \in D, e' \in E'_d \tag{3}$$

$$y(d, e', p) \leqslant \frac{1}{W_d} \sum_{w \in W} x(d, e', p, w), \forall d \in D, e' \in E'_d, p \in P_{\{e',d\}} \tag{4}$$

$$z(d) \leqslant \frac{1}{|E'_d|} \sum_{e' \in E'_d} \sum_{p \in P_{\{e',d\}}} y(d, e', p), \forall d \in D \tag{5}$$

Objective function is represented by equation 1; it aims at maximizing the number of virtual infrastructures to be allocated. The factor α_d is a pondering factor to represent operator's policies. Then, expressions 2, 3, and 4 represent the constraints in order to ensure that not two virtual links are built on top of the same wavelength, that at most W_d different wavelengths are assigned to every virtual link in d, and that every wavelength requested by a virtual link e' is routed through the same path. Finally, constraint in 5 discriminates whether demand d is satisfied or not.

In order to better illustrate the ILP formulation and the constraints, the following figures have been introduced. Figure 23 depicts the constraint 2, which determines that not two virtual links are built over the same wavelength. In the example, there are two demands requesting one wavelength per virtual link, and the physical substrate contains a physical link with two wavelengths available, i.e. $w1, w2$. Basically, constraint 2 retains both demands to be allocated over $w1$ or $w2$, so both virtual links cannot be built on top of the same wavelength.

On the other hand, Figure 24 displays how at most W_d wavelengths are assigned to every virtual link in the demand. For example, there is one demand requesting one wavelength, which is allocated over

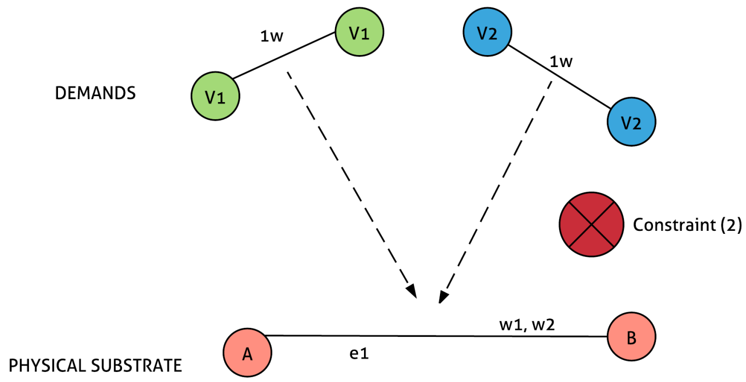

Figure 23: Constraint 2 example

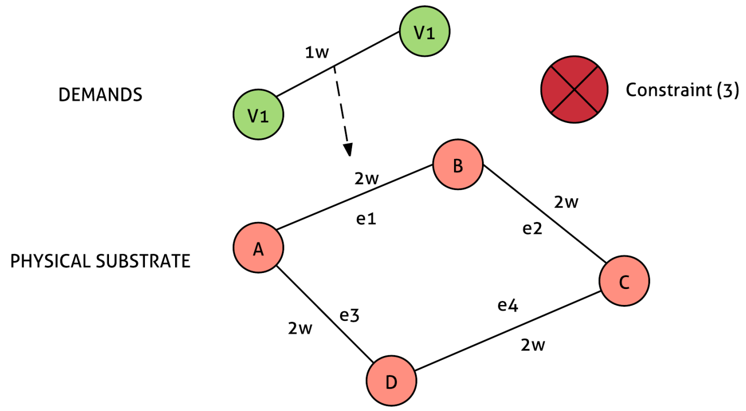

Figure 24: Constraint 3 example

the available physical link $e1$ that contains two different wavelengths. Constraint 3 ensures that only one wavelength (the one requested in this example) will be allocated to the virtual link within the demand. Physical substrate considered in this figure consists of four nodes, connected through physical links with two available wavelengths each link.

Finally, while Figures 23 and 24 might seem obvious, Figure 25 represents the most interesting constraint taken into account within the fixed allocation problem. It displays constraint 4, which guarantees that all the wavelengths within a virtual link e' are routed through the same path. In the upper part of the figure it is displayed one demand with one virtual link requesting three wavelengths. In the bottom part of the figure, in blue, it is shown the possibility of routing two wavelengths of the virtual link over the physical links $e1, e2$ and the other wavelength over $e3, e4$. Precisely, constraint 4 avoids this situation, since it guarantees that all the wavelengths of the same virtual link are routed through the same path. It is worth to mention

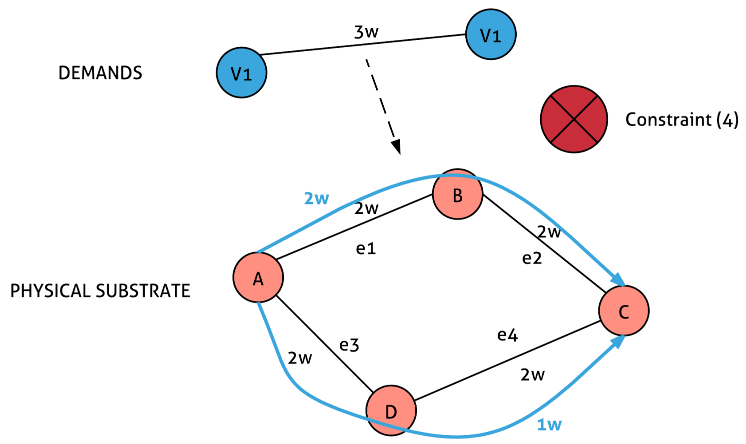

Figure 25: Constraint 4 example

that continuity constraint is implicit in the variable definition of the problem.

4.1.2 *Flexible Allocation*

The flexible grid architecture allows to efficiently serve low data-rate sub-wavelength transmissions

The flexible grid architecture allows to efficiently serve low data-rate sub-wavelength transmissions, on the one hand, and, on the other, ultra-high capacity super-wavelength transmissions onto the available network spectral resources, but poses new challenges compared to the classical Routing and Wavelength Assignment (RWA) problem applicable to WSONs. Instead of wavelengths, a contiguous spectrum portion has to be allocated in flexible optical networks. Moreover, given a lack of spectrum conversion capabilities in the network, the assigned spectrum portion must show a continuity between the remote endpoints of the incoming connection requests (i.e., VON neighbouring nodes in this work). Both constraints, namely, spectrum contiguity and continuity constraints, must be ensured by the Routing and Spectrum Allocation (RSA) algorithm in the network.

It is assumed that the usable bandwidth of an optical fibre can be discretized into multiple FSs [KW11] and so, the bandwidth requested by a demand can be converted into a number of FSs. The ILP formulation for the flexible allocation is based also in the one presented in [KW11]. The definitions for the paths sets presented for the fixed case remain the same here. Besides, we define $F = \{f_1, f_2, ..., f_{|F|}\}$ as the ordered set of available FSs per physical link and F_d as the number of FSs per virtual link desired by demand $d \in D$. The problem variables are:

$x(d, e', p, f) = \{1$ if FS f in path p is selected to be the lowest indexed slot assigned to virtual link e' in demand d, 0 otherwise$\}$;

$y(d, e', p, f) = \{1$ if FS f in path p is assigned to virtual link e' in demand d, 0 otherwise$\}$;

and $z(d) = \{1$ if demand d can be satisfied, 0 otherwise$\}$.

Then, the ILP formulation is as follows:

$$\max \sum_{d \in D} \alpha_d z(d), \text{s.t.} \tag{6}$$

$$\sum_{p \in P_{\{e',d\}}} \sum_{f \in F} x(d, e', p, f) \leqslant 1, \forall d \in D, e' \in E'_d \tag{7}$$

$$\begin{aligned} x(d, e', p, f_i) \leqslant y(d, e', p, f_j), \quad & \forall d \in D, e' \in E'_d, p \in P_{\{e',d\}}, \\ & f_i, f_j \in F, i = 1, \ldots, |F| - F_d + 1, \\ & j = i, \ldots, i + F_d - 1 \end{aligned} \tag{8}$$

$$\begin{aligned} x(d, e', p, f_i) = 0, \quad & \forall d \in D, e' \in E'_d, p \in P_{\{e',d\}}, \\ & f_i \in F, i = |F| - F_d + 2, \ldots, |F| \end{aligned} \tag{9}$$

$$\sum_{d \in D} \sum_{e' \in E'_d} \sum_{p \in P_{\{e',e\}}} y(d, e', p, f) \leqslant 1, \forall e \in E, f \in F \tag{10}$$

$$\sum_{p \in P_{\{e',d\}}} \sum_{f \in F} y(d, e', p, f) \leqslant F_d, \forall d \in D, e' \in E'_d \tag{11}$$

$$z(d) \leqslant \frac{1}{|E'_d|} \sum_{e' \in E'_d} \sum_{p \in P_{\{e',d\}}} \sum_{f \in F} x(d, e', p, f), \forall d \in D \tag{12}$$

Objective function 6 seeks to maximize the number of virtual infrastructures to be allocated in the underlying optical network. Factors α_d have the same role as before. Constraints 7 serve the purpose of selecting for every virtual link $e' \in E'_d$ a unique path from the candidate paths set and a FS to be the lowest indexed slot assigned to the virtual link. Constraints 8 are the contiguous FS assignment constraints. If slot f_i is selected as the lowest indexed slot for virtual link e', the consecutive $F_d - 1$ slots should be assigned to this virtual link. Constraints 9 ensure that any FS selection option will have enough space in the frequency spectrum, if chosen. Constraint 10 are the spectrum clashing constraints, avoiding that two virtual links are supported over the same FS in the same physical link. Constraints 11 ensure that at most F_d different FSs are assigned to every virtual link of demand d. Constraints 12 discriminate whether demand d is satisfied or not.

In order to better illustrate contiguous FS assignment constraint, Figure 26 and Figure 27 have been included. That constraint ensures that if slot f_i has been selected as the lowest indexed slot for a given virtual link, the consecutive slots must be assigned to the same link. Consider the situation displayed in Figure 26, where there is a physical link with six available FSs, and there are two demands composed of one virtual link each, requesting capacity for four FSs and two FSs respectively. Basically, by means of constraint 8, it is guaranteed that the situation depicted in Figure 27 will never occur, since all the frequency slots assigned to a given virtual link must be consecutive. This means that the four slots coming from the first demand will be allocated consecutively over the first four available FSs - lower available index; while the two frequency slots from the second demand will be allocated in the last two FSs. Guard intervals between sub-carriers are not depicted in the Figures.

Contiguous assignment constraint ensures that consecutive slots are assigned to the same virtual link

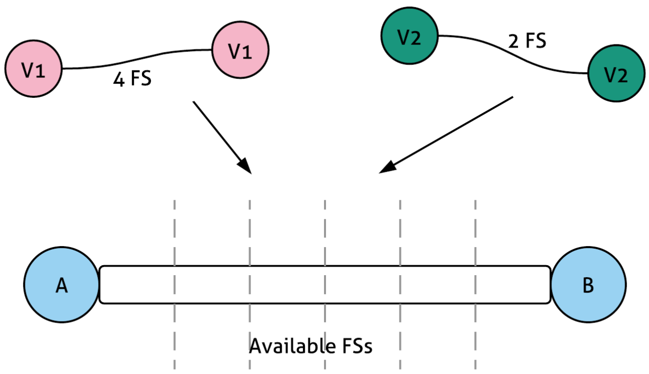

Figure 26: Available FSs in the physical substrate and two demands example

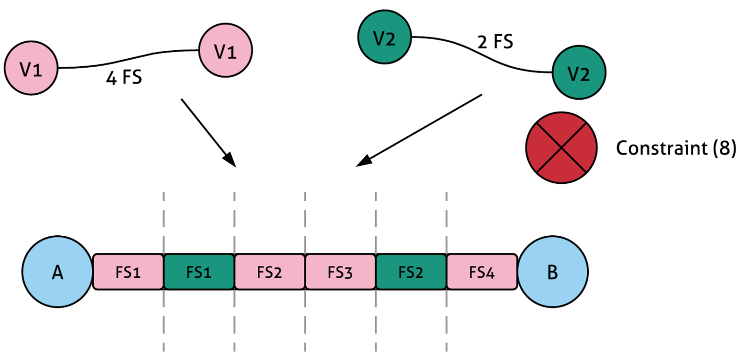

Figure 27: Constraint 8 example

4.2 RESULTS AND DISCUSSION

To analyze the impact of the underlying physical technology used by the substrate network on the number of VONs that can be allocated, we have executed series of experiments using both Fixed and Flexible allocation models. The experiments have been executed on the 16-Node EON core network topology [MCL+03], assuming that every physical link has a usable bandwidth of 400 GHz. In the fixed-size grid scenario, following a grid with a 50 GHz channel spacing, it results in 8 wavelengths per link; in the flexible grid scenario, considering a FS width of 6.25 GHz, it results in 64 FSs per link.

In particular, $|D|$ sizes from 5 to 25, in steps of 5, have been considered, assuming for both models that all factors $\alpha_d = 1$, that is, regardless of its size or the spectral resources demanded, all VONs are treated equally, there is no preference for any specific demand. Moreover, we have fixed the number of candidate paths per virtual link to the first 6 shortest paths using the distance in hops as the metric, so as to avoid excessive execution times for the models. Although the presented results may not match the optimal ones in some occasions, the presented formulations are still valid and the absolute optimal could be obtained if the whole set of candidate paths per virtual link is considered.

The generation of the demand sets for all experiments throughout this chapter follows a 3-step process. Firstly, 3 or 4 physical network nodes are randomly selected as virtual nodes for each demand. In this way, we obtain reasonable medium-sized virtual networks compared to the underlying physical network size. Next, the selected virtual nodes are then randomly connected using the Erdős-Rényi algorithm [CMP+10], here slightly modified to prevent the generation of non connected graphs (any connected connectivity matrix is generated with equiprobability). The minor modification avoids that probability zero (non-connected node) is generated.

Finally, the bandwidth requested by the demand in GHz is selected from the set $25, 50, 100$ with probabilities of 0.4, 0.4 and 0.2, respectively. The set comes from an example of nominal central frequencies of the Dense Wavelength Division Multiplexing (DWDM) grid [Itu02]. In the fixed-size grid scenario such bandwidth requests are translated to 1, 1 and 2 wavelengths. In the flexible grid scenario they are equivalent to 4, 8 and 16 FSs. We assume that any guard band needed by the physical equipment to perform correctly the switching between demands is included in the bandwidth requested by them.

The execution of the exact ILP formulations without any heuristic, considering only the first six shortest paths obtained using the distance in hops as the metric, have been averaged over 100 executions, randomly generating a new set of demands at the beginning of each execution. The experiments have been launched on Intel

Core2 Quad at 2.66 GHz PCs with 4 GB RAM memory. The optimization software used for all executions is IBM ILOG CPLEX Optimizer v.12.2 [IBM10]. The idea of the experiments performed was twofold: on the one hand, to analyze the number of virtual infrastructures allocated, or inversely, the number of virtual infrastructures not allocated, i.e. Blocking Probability (BP); on the other hand, to analyze the complexity of both models, in terms of constraints and variables.

Regarding the complexity of the models, and considering the aforementioned assumptions, it can be concluded that the complexity of both models is closely related to the size of the set of candidate paths for the virtual links. In more detail, in the Fixed-Virtual Optical Network Allocation (VONA) model, the number of decision variables is in the order of $\mathcal{O}(|D||\bar{E}'_d||\bar{P}_{\{e',d\}}||W|)$ and the number of constraints is in the order of $\mathcal{O}(|E||W| + |D||\bar{E}'_d||\bar{P}_{\{e',d\}}|)$, being $|\bar{E}'_d|$ the average number of virtual links per demand, and $|\bar{P}_{\{e',d\}}|$ the average number of candidate paths per virtual link. We can see that the main contributions to the complexity of fixed allocation problem are the wavelength clashing constraints (2) and the unique path constraints (4).

In the flexible model, the number of decision variables is in the order of $\mathcal{O}(2|D||\bar{E}'_d||\bar{P}_{\{e',d\}}||F|)$ and the number of constraints is in the order of $\mathcal{O}(|D||\bar{E}'_d||\bar{P}_{\{e',d\}}||F||\bar{F}_d|)$, being $|\bar{F}_d|$ the average number of FSs requested by the demands. Therefore, the main contributions to the complexity of flexible approach is the large number of FSs in some network scenarios, resulting in a huge number of contiguity constraints (8).

To exemplify the complexity of both formulations, Table 1 displays the value of these expressions for the scenario considered in the executions, both variables and constraints, plus the average execution time of both models. Table 1 shows that the complexity of Flexible approach, in terms of number of variables and constraints, is substantially greater than the one of Fixed scheme. This comes from the fact that the number of FSs in the flexible grid scenario is substantially larger than the number of wavelengths in the fixed-size grid scenario. Besides this, the spectrum contiguity constraints add a considerable complexity to the problem. Focusing on the execution times of Flexible, they notoriously increase with the size of D. Hence, an heuristic for the flexible grid scenario might be necessary when dealing with large scenarios as the the execution of the exact ILP formulation becomes impractical. The study and development of an heuristic for the flexible grid scenario was out of the scope of this contribution, and thus it was left out of the work.

As an example of the complexity calculation for the ILP formulation, for the case $|D| = 5$, in the fixed scenario, we have that the number of decision variables comes determined by $(|D||\bar{E}'_d||\bar{P}_{\{e',d\}}||W|)$, whereby $|D|$ is equal to five, $|\bar{E}'_d|$ is the average number of virtual links in the demands, and it is equal to 3,5 (refer to the aforemen-

Table 1: Complexity of the models

	Fixed			Flexible		
	Variables	Constraints	Time (s.)	Variables	Constraints	Time (s.)
$\vert D\vert = 5$	840	289	0.272	13440	53760	2.37
$\vert D\vert = 15$	2520	499	3.28	40320	161280	1.25×10^4
$\vert D\vert = 25$	4200	709	18.03	67200	268800	7.29×10^4

tioned demand generation description considering three or four virtual nodes, interconnected with equiprobability), $|\bar{P}_{\{e',d\}}|$ is equal to six, since we only consider the first six available shortest paths, and in the worst case there will be always six candidate paths, and $|W|$ is equal to eight, which gives a total amount of 840 decision variables (5)x(3,5)x(6)x(8). For the number of constraints, it comes determined by $(|E||W| + |D||\bar{E}'_d||\bar{P}_{\{e',d\}}|)$, whereby $|E|$ is the number of physical links in the 16-Node EON topology considered, i.e. 23, and thus we have $[(23)\text{x}(8) + (5)\text{x}(3,5)\text{x}(6)] = 289$ constraints within the problem.

As for the results obtained through the executions of both models, i.e. the execution of the exact ILP formulations without any heuristic, considering only the first six shortest paths obtained, Figure 28 shows the BP of the demands as a function of the size of the demand set. We can observe that the flexible grid scenario provides a lower BP figure (i.e. allocates a larger number of VONs) than the fixed-size grid scenario, being the difference more notorious as $|D|$ increases(e.g., we can observe a difference in BP of around 1.1% for $|D| = 10$ while a difference of around 8% is observed for $|D| = 20$).

Flexible grid scenario allocates a larger number of virtual infrastructures than the fixed-size grid scenario

This capacity of being able of allocating a larger number of VONs in the flexible grid scenario is due the fact that its granularity is finer than the fixed-grid scenario's granularity, making it possible to adjust more to the bandwidth needs of the demands. Focusing on the traffic profile considered for the experiments, for the demands requesting 25 GHz, the flexible grid scenario allocates exactly 25 GHz (i.e. 4 FSs) of spectrum to these demands, while in the fixed-size grid scenario, due its coarser granularity, it allocates 50 GHz (i.e. 1 wavelength) of spectrum to these demands, adding an overhead of 100%. Basically, the fixed case is not capable of allocating any unit below one wavelength, which is also the slicing considered as the slicing unit; while the flexible case holds finer granularity thanks to the frequency slots.

The capacity of the flexible grid scenario to allocate more VONs than the fixed-size grid could be potentially greater for traffic profiles where the disparity between the requested bandwidth by the demands and the channel spacing in the fixed-size grid scenario is big, either for sub-wavelength or super-wavelength traffic demands.

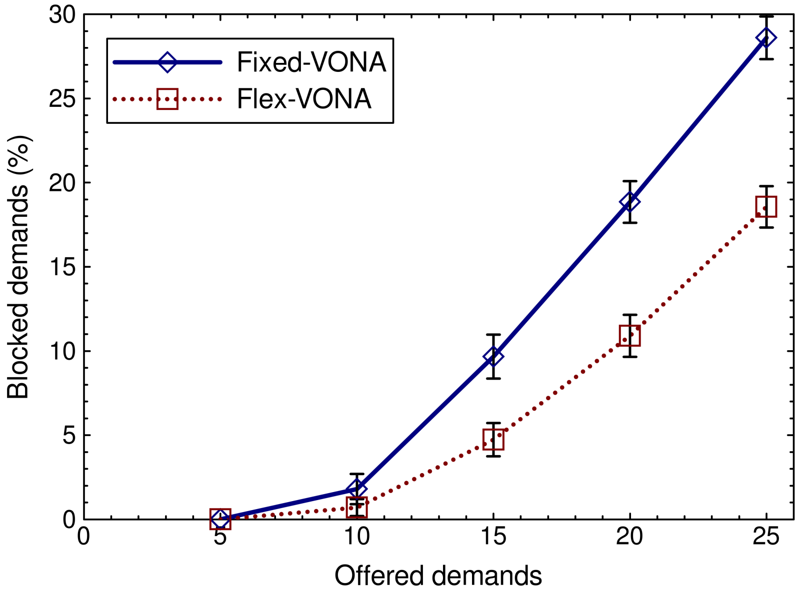

Figure 28: Blocking probability as a function of the size of the demand set.

4.3 conclusion

In this chapter it has been analyzed the virtual infrastructure allocation problem, which has been introduced as a mean to describe formally the problem of how to map a set of VONs into a given optical network substrate with finite resources, while accounting for the particularities imposed by the optical medium. Depending on the technology used by the physical substrate, more or less VONs can be accommodated into the transport network.

To analyze the impact of this issue, we have considered two transport technologies as cases of study, wavelength switching and spectrum switching respectively. Exact ILP formulations for both scenarios have been proposed in aims to optimally allocate a set of VONs into a substrate using these technologies. We have validated the proposed formulations through a series of experiments, reaching the conclusion that for demands that require a fine granularity in terms of bandwidth, the spectrum switching alternative could be the more appropriate technology.

This first contribution of the thesis demonstrated the importance of considering the different physical characteristics of the substrate where the virtual infrastructures will be allocated. This demonstrates to be of fundamental importance for optical networks, when considering both fixed grid and flexible grid scenarios. The sub-lambda virtualization, with greater flexibility, will become of crucial importance when converging wireless access networks with fixed networks. Results in terms of maximizing the number of virtual infrastructures clearly demonstrate that greater flexibility in the substrate allows the infrastructure provider to provision more VIs.

5 CLUSTERING VI REQUESTS

Balk logic with acquaintance that you have,
And practice rhetoric in your common talk;
Music and poesy use to quicken you;
The mathematics and the metaphysics—
Fall to them as you find your stomach serves you.
No profit grows where is no pleasure ta'en;
In brief, sir, study what you most affect.
- TRANIO, Scene I (The Taming of the Shrew)

Chapter 3 provides an overview of the problem analyzed during the dissertation. In detail, Figure 18 contains the different elements involved in the problem; i.e. the virtual infrastructure request, the physical substrate considered, and, later on within chapter 3 explained, the policy upon which the VI is provisioned. Previous chapter 4 provides an overview of the problem when considering different physical substrates. Basically, it analyzes the problem of maximizing the number of VONs as a function of the physical characteristics of the substrate.

This chapter provides an insight on another element of the problem: the virtual infrastructure requests. The work presented in this chapter is the result of a joint collaboration based on a previous publication [DLBDM12]. The collaboration produced [RGEF+12], and [GERF+12].

Virtual infrastructure requests are treated independently without any pre-processing

Usually, requests are treated independently, and there is no pre-processing at all. However, in case we consider an offline problem, i.e. all the requests are known in advance, there are some processes which could optimize later on the scalability of the control plane to be deployed over the different VIs. For example, grouping together some of the requests, although the approach does not consider complete isolation between the virtual infrastructures themselves.

Typically, clustering is defined as the task of assigning a set of objects into groups, the so called clusters, so that the objects in the same cluster are more similar in any sense to each other than those in other clusters. On the other hand, in DWDM scenarios, virtual infrastructure topologies consist of lightpaths where each virtual infrastructure can be managed independently.

Essentially, through virtualization, it is enabled physical infrastructure sharing, without interference between the different deployed VIs. This concept is usually referred to as isolation, and creates a desirable working environment for the different virtual infrastructure operators in order to provide services on top of such virtual infrastructures. For instance, large fluctuations in traffic load, misconfigured devices, malicious users, etc. in one virtual network have no effect on the other virtual infrastructures.

However, isolation constraints between virtual infrastructures usually leads to an increase in required capacity with respect to the physical optimal infrastructure. Given the coarse bandwidth granularity in current commercial DWDM products (each wavelength offers 10, 40, or 100Gbps), total network capacity may be very high while resource utilization unacceptably low.

5.1 PROBLEM STATEMENT

Whereas current Physical Infrastructure Providers (PIPs) usually operate their own networks, this could change so that PIPs could offer virtual infrastructures which they do not operate themselves. Instead, a different entity, the virtual infrastructure operator or Virtual Infrastructure Operator (VIO), is responsible for the correct operation of this virtual network, without actually owning the physical equipment. The operation of the virtual infrastructure is performed through the corresponding Network Control Plane (NCP), which is the component responsible for the control of the VI, including service provisioning and monitoring. Each VIO may deploy one NCP per VI. No virtual infrastructure can be effectively operated without NCP.

Clustering of requests could be applied in order to optimize resource utilization

The roles mentioned here are directly derived from the layered GEYSERS or CONTENT architectures, as detailed within Appendix A. Like mentioned above, this sharing of the substrate requires isolation between different virtual infrastructures.

Some researchers have proposed novel business models whereby physical network operators sell their network infrastructure to one or more virtual network providers. This may indeed lead to novel scenarios and applications. However, in order to maintain complete isolation between individual customer's VI requests may be a wasteful process in terms of resource utilization.

Using as a basis the formulation proposed in [DLBDM12], we proposed to cluster VI requests. Thus, isolation within clusters is not enforced, although full isolation is enforced between different clusters. A small number of isolated virtual infrastructures maximizes the opportunities of statistical multiplexing and as such will lead to the highest resource utilization. Figure 29 depicts clearly the clustering process between virtual infrastructure requests.

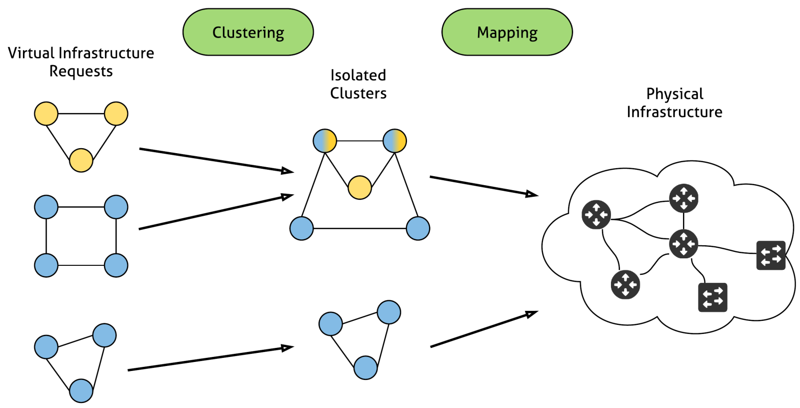

Figure 29: Clustering process considering three virtual infrastructure requests and two clusters

In Figure 29 it can be observed how the two first virtual infrastructure requests are clustered into one single request, which has consequently to be mapped over the physical infrastructure. However, this clustering will lead to large isolated virtual networks that in turn will degrade NCP scalability, since the number of control plane messages is directly influenced by the number of nodes in the network. Formally, the embedding problem solved can be defined as follows

Given

- Physical infrastructure topology
- Set of virtual infrastructure requests, each one of them specified as an adjacency matrix
- The number of isolated virtual infrastructure clusters that should be mapped on the physical topology. Each isolated cluster is composed of one or more virtual infrastructure requests.

Find

- The composition of isolated clusters, i.e. which VI requests jointly form what isolated cluster.
- The mapping of each isolated cluster on the physical topology.

5.2 PROBLEM SOLUTION AND RESULTS DISCUSSION

The proposed solution to this problem by all the co-authors in [RGEF+12], and [GERF+12] comprised a two-step algorithm: first, clustering to group individual VI requests in groups of independent clusters is performed, after which we determine the mapping of these clusters on to the physical network, basing the exact topology of each cluster on the aggregate network demand of all involved requests.

For clustering, it has been utilized an ILP-based formulation such as the one in [DLBDM12][a] also. Such algorithm provides optimal results for the clustering, compared to a random clustering approach also utilized.

The clustering algorithm groups virtual infrastructure requests that are most similar. Such similarity could be based on different criteria such as node activity (i.e. nodes where data traffic is generated or received), or link overlap (i.e. requests that have the highest number of overlapping links in the physical topology). The ILP formulation from Appendix B only considered node activity, i.e. its objective is to cluster requests that have the highest number of actives nodes in common.

The solution comprises a two-step algorithm: clustering and mapping

The virtual network design or allocation phase is then executed for the different clusters. Two proposals are considered also regarding the actual mapping onto the physical infrastructure, which correspond to the extremes of the potential objectives for analyzing the control plane scalability. (i) a *FullMesh* strategy, which minimizes hop distance between the virtual infrastructure nodes, and (ii) a *MaxUtil* strategy that aims at filling the available link capacity as efficiently as possible, by maximally exploiting statistical multiplexing.

A complete description of both algorithms is presented in Appendix C. The algorithms considered have been selected because they represent the extremes of the potential objectives. In fact, a small number of isolated virtual infrastructures maximizes the opportunities of statistical multiplexing and as such should lead to the highest resource utilization results. However, at the same time this might lead to large isolated virtual networks that in turn degrade control plane scalability, since the number of control plane messages is directly influenced by the number of nodes in a virtual infrastructure.

The control plane messaging model is not considered into this contribution, which focuses on the physical resource utilization as a function of the clustering during the pre-processing stage and the strategy for allocation of the clusters with the two strategies. The reader is referred to [DLBDM12] for the complete control plane messaging model and analysis.

In order to obtain the results of the analysis, the physical topology defined in the COST 239 basic European network was utilized. It consists of 28 nodes and 41 bidirectional links [O'M96]. The topology utilized is considered a reference physical topology for European-wide optical network. It provides a realistic example of long-haul optical network, both in terms of nodes and capacities.

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a Details on the ILP formulation for clustering are provided in Appendix B. Please refer to the Appendix for a complete specification of the formulation utilized. The ILP formulation is not direct part of the contribution, since it was only utilized in order to analyze the impact of the approach. The major part of the contribution consisted of defining the clustering approach, as well as the functional analysis of such a two-step algorithm approach

Virtual infrastructure requests are generated by random selection out of all physical nodes of A active nodes that will generate the traffic, i.e. random selected nodes in the matrix representing the demand will be generating traffic; the remaining nodes in the traffic matrix will not generate any data traffic, i.e. will hold $\lambda_{ij} = 0$. For the non-zero arrival and holding rates, we considered a generation according to an exponential distribution with means $\lambda_{ij} = \frac{1}{A(A-1)}$ and $\mu_{ij} = 1$ (see note[b]).

To ensure fair comparison considering the random selection of active nodes, please note that the aggregate traffic load is constant over all scenarios by the weighting of the arrival rates with the number of traffic pairs. 20 virtual infrastructure requests are generated, and the target blocking probability is set to 1%. Each data point in the following graphs is the result of averaging over 20 experiments with randomly generated virtual infrastructure requests.

Finally, in the following graphs, a value of $k = 1$ corresponds to the case where no virtualization is considered, while $k = 20$ implies full isolation (no clustering), i.e. each virtual request is allocated its own resources.

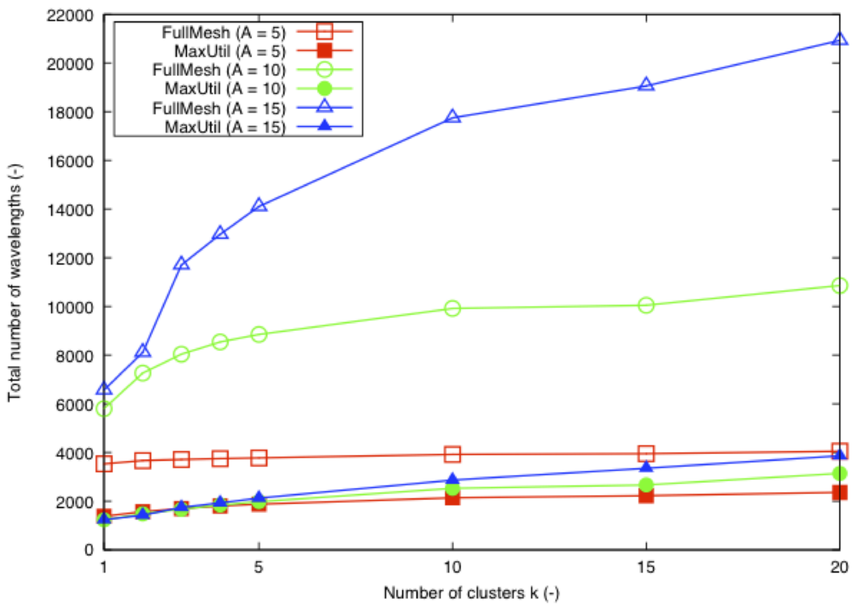

Figure 30: Number of wavelengths of ILP-based over random clustering

Figure 30 and 31 contain the results obtained through the grouping requests approach after the executions above described. Figure 30 shows the total number of wavelengths necessary to instantiate a varying number of virtual network clusters (here denoted as k), using the ILP-based clustering algorithm and as a function of the active nodes within A. We observe the relatively slow growth in wavelength

b Please refer to the appendix B for further details on A, λ, and μ

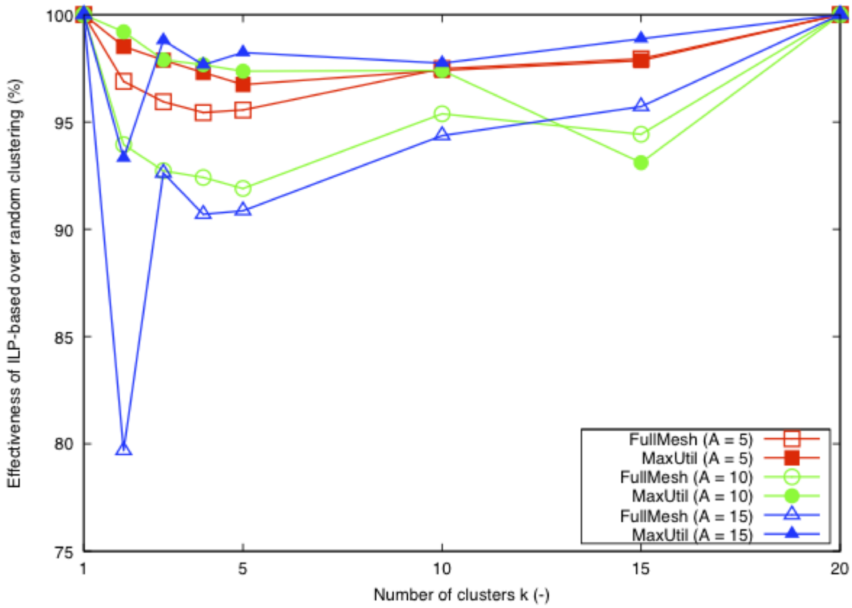

Figure 31: Ratio of total wavelength capacity (effectiveness) of ILP-based over random clustering

usage for the *MaxUtil* approach, which is in stark contrast to the behaviour of the *FullMesh* virtual infrastructure design. Furthermore, the number of actives nodes A in each virtual infrastructure request has relatively little effect on the *MaxUtil* approach.

Figure 31 shows the ratio of the total number of wavelengths for the ILP-based over random clustering. Obviously, identical results are obtained when $k = 1$ and $k = 20$, i.e. when there is no or full virtualization. Clearly, most cases show that the ILP algorithm requires 5 to 10% less wavelength capacity compared to random clustering. Also, the effectiveness of the random clustering reaches a minimum between $k \in [3, 6]$ clusters, indicating the region where intelligent clustering is most in order. However, the relatively low improvement of ILP-based over random clustering indicates that more advanced clustering should be developed. Indeed, the approach only incorporated node activity of virtual infrastructure requests, whereas the potential for, for instance, network grooming was not considered. Also, since the study in this contribution completely focused on random virtual network requests, their correlation is limited and as such opportunities for intelligent clustering are most likely rare.

5.3 CONCLUSION

Although isolation is considered to be an strict requirement when dealing with virtualization, there might be some business cases where isolation could be relaxed. For example, there might be a case where a single VIO requests for more than one virtual infrastructure. In these cases, a pre-processing procedure in the requests such as clustering might be relevant in order to reduce the total amount of physical infrastructure utilized.

In fact, the obtained results indicated that the need for network resources can be reduced around 10% by means of clustering the different virtual infrastructure requests, at the same time the design of the control plane is taken into account within the mapping process.

In detail, the analysis performed demonstrated that the number of wavelengths utilized in order to allocate the requests for a varying number of clusters remains stable in the case of *MaxUtil*, since it aims at maximizing the utilization of the resources. At the same time, the approach is not much affected by the increase of active nodes in the demands. On the other hand, the *FullMesh* approach consumes as expected a major number of wavelengths in all the cases.

Finally, in terms of effectiveness, it is observed that in all the cases the proposed clustering algorithm, based on active nodes, outperforms the random clustering, which reaches a minimum between $k \in [3, 6]$ clusters, indicating the region where intelligent clustering is most in order.

6 SAVING ENERGY THROUGH GREEN-VI PROVISIONING

> The past is always with us. Where we come from, what we go through, how we go through it; all this shit matters. Like at the end of the book, ya' know, boats and tides and all. It's like you can change up, right, you can say you're somebody new, you can give yourself a whole new story. But, what came first is who you really are and what happened before is what really happened
> D'Angelo Barksdale, The Wire

It is estimated that Information and Communications Technologies (ICT) accounts for the 4.7% of the primary energy consumption worldwide [VHLL+14, Con13, GC15]. As mentioned in Chapter 1, the expansion of the Internet in size and complexity incurs increased energy consumption of both IT and network resources, thus leading to an acute interest in energy efficiency networking [BAH+09]. IT resources require very high levels of power consumption for their operation and their conventional operating window is commonly not optimized for energy efficiency. Hence, building virtual infrastructures in an energy aware manner through a relatively low energy consuming optical network infrastructure is expected to offer significant energy savings. Energy efficiency from the virtualization perspective could be targeted in both VI planning phase and the VI operation phase. This chapter focuses on the planning phase, where it is decided where to allocate the current lightpaths to serve the IT demands from the different IT resources.

It is estimated that ICT accounts for the 4.7% of the primary energy consumption worldwide

6.1 ENERGY MODELS FOR IT AND NETWORK RESOURCES

The estimation of energy consumption of the network resources is highly sensitive to the network architecture employed and the network technology used. Considering the context of this contribution, which focuses on optical networking resources utilizing WDM technologies, the overall network power consumption model is based on the power-dissipating or active elements of the resource and transmission line related elements. Basically, all the OXCs utilized within this contribution are based on the Wavelength Selective Switch (WSS) architecture using Micro-Electrical Mechanical Systems (MEMSs), and they do not hold wavelength conversion capabilities. The fibre links use a model comprising a sequence of alternating single mode fibre and dispersion compensating fiber spans together with optical amplifiers to compensate for the losses. Further details could be found within in [TKP+11].

On the other hand, the IT resources considered in this study were basically data centres providing processing data and data storage services. The model for such an infrastructure is a liner power consumption model that mainly concentrates on the power consumption associated with the CPU load of the equipment, based on [KL11]. More specifically, p_s is referred to the CPU resources and E_s to the energy consumption for utilizing a portion $u_s = p_s/p_s^{max}$ of the maximum CPU capabilities, p_s^{max}, of server s. For simplicity, the following linear energy consumption model has been adopted [Dav]

$$E_s(u_s) = P^s_{idle} + (P^s_{busy} + P^s_{idle})u_s$$

whereby P^s_{idle} and P^s_{busy} represent the energy consumption of the server s at idle state and under full load respectively. For further details regarding the technical specifications of the IT servers the reader is referred to [Corb, FWB07, Dav].

In addition to the power consumption of both kind of resources, a 100% overhead due to cooling elements was incorporated to the energy consumption model.

The objective of the planning is to identify the topology and determine the virtual resources required to implement VIs

6.2 PROBLEM FORMULATION

The VI planning process, within the whole VI provisioning service, could be seen as the process necessary to determine the optimal design of the VI itself based on a set of requirements (e.g. historical operating data, estimated future Virtual Resources (VRs) requirements, or others). Basically, the objective of the planning process is to identify the topology and determine the virtual resources required to implement such VI. In the case of this contribution, the VI will not only satisfy customer's specific needs and requirements, but it will also satisfy the virtual infrastructure provider's requirements regarding energy consumption. The planning problem has been formulated as a mixed ILP, which aims at minimizing jointly the total energy that is consumed by the different resources, i.e. the network and the IT resources. Due to the aforementioned energy consumption models, the problem has to be formulated as a mixed ILP.

The single virtual infrastructure planning problem is formulated using a network that is composed of one resource layer that contains the physical infrastructure and will produce as an output a given virtual infrastructure layer. The problem is suitable for the planning of the virtual infrastructure layer over an integrated IT and optical network infrastructure.

The physical substrate considers optical network resources. The motivation behind considering converged optical-IT networks in this contribution comes, as described in Chapter 1 from the set of critical applications and new emerging ones which demand highly reliable, robust, and secure network. At the same time, there are many infrastructure challenges on the arena in order to bring optical networks together with the Cloud, such as the fact that there is a huge increase in the numbers of users/applications and a rapid increase in available bandwidth for users beyond 1Gbps, as well as applications requesting 10Gbps [DPC+10, ENJ+10].

The physical infrastructure is described through an eleven-node topology in which randomly selected nodes generate demands $d = (1, 2, \ldots, D)$ to be served by a set of IT servers $s = (1, 2, \ldots, S)$. Reduced eleven-node topology utilized is later described and justified in next sub-section. It is based on the COST 239 reference network. The granularity of the demands is the wavelength. The IT locations (demand destinations) at which the services will be handled, are not specified and are of no importance to the services themselves.

The binary variable a_{ds} is introduced to indicate whether demand d is assigned to server s or not and it equals 1, if and only if demand d is processed on server s. It is assumed that each demand can be assigned to only one server:

$$\sum_s a_{ds} = 1 \quad d = 1, 2, \ldots D \tag{13}$$

For each demand d, its demand volume h_d is realized by means of a number of lightpaths assigned to paths of the VI. Let $p = 1, 2, \ldots P_{ds}$ be the candidate path list in the VI for the lightpaths required to support demand d at server s and x_{dps} the non-negative number of lightpaths allocated to path p. The following demand constraints should be satisfied in the VI:

$$\sum_s \sum_p a_{ds} x_{dps} = h_d \quad d = 1, 2, \ldots, D \tag{14}$$

Summing up the lightpaths through each link $e = (1, 2, \ldots, E)$ of the VI we can determine the required link capacity y_e for a given link e:

$$\sum_d \sum_s \sum_p \delta_{edps} x_{dps} \leqslant y_e \quad e = 1, 2, \ldots, E \tag{15}$$

whereby δ_{edps} is a binary variable defined as follows:

$$\delta_{edps} = \begin{cases} 1, & \text{if link } e \text{ of VI belongs to path } p \text{ realizing demand } d \text{ at } s \\ 0, & \text{otherwise} \end{cases}$$

(16)

Using the same rationale, the capacity of each link e in the VI is allocated by identifying the required lightpaths in the PI. The resulting PI lightpaths z determine the load of each link $g = (1, 2, \ldots, G)$, and hence its capacity h_g. Assuming that $q = 1, 2, \ldots, Q_e$ is used for denoting the PI candidate path list realizing link e, the following demand constraint for link e should be satisfied:

$$\sum_q z_{eq} = y_e \quad e = 1, 2, \ldots, E \tag{17}$$

where the sum is taken over all paths q on the routing list Q_e of link e. Introducing the link-path incidence coefficients for the PI

$$\gamma_{geq} = \begin{cases} 1, & \text{if link } g \text{ of PI belongs to path } q \text{ realizing link } e \text{ of VI} \\ 0, & \text{otherwise} \end{cases} \tag{18}$$

the general formula specifying the PI capacity constraint can be stated as:

$$\sum_c \sum_q \gamma_{geq} z_{eq} \leqslant u_g \quad g = 1, 2, \ldots, G \tag{19}$$

where G is the total number of links in the PI and the summation for each link g is taken over all lightpaths in the PI.

Apart from link capacity constraints defined in equation 15 and equation 19 for the VI and the PI respectively; the total demands that are assigned to each server should not exceed its capacity p_s. The latter capacity corresponds to the underlying resources, such as CPU, memory, or even disk storage. The inequality specifying servers capacity constraint is given by

$$\sum_d \sum_p a_{ds} c_{ds}(x_{dps}) \leqslant p_s \quad s = 1, 2, \ldots, S \tag{20}$$

where the summation is taken over all demands that arrive at server s and $c_{ds}(x_{ds})$ is a parameter specifying the computational requirements for demand d on server s. The objective of the current problem formulation is to minimize the total cost of the resulting network configuration as this cost consists of the following components:

- k_s that is the cost of the capacity of link g of the PI. It consists of the energy consumed by each lightpath due to transmission and reception of the optical signal, optical amplification at each fiber span and switching according to the model described in [TKP+11].

- E_s that is the cost for using capacity p_s of the IT servers. The linear energy consumption model has been described previously.

In this context, minimum energy consuming VI is obtained by minimizing the following cost function

$$\text{Minimize} \quad F = \sum_g k_g u_g + \sum_s E_s(u_s) \tag{21}$$

The above Mixed-ILP has been solved analytically employing the methods of Lagrangian relaxation and dual decomposition [APC08].

6.3 NUMERICAL RESULTS

In order to investigate the energy efficiency of the proposed VI provisioning scheme, this contribution considered the GEYSERS architecture, as illustrated in Figure 60. For the physical infrastructure a reduced version of the COST 239 Pan-European reference topology [O'M96], as in Chapter 5, has been utilized, in which four randomly selected nodes generate demands to be served by two IT server located in Luxembourg and Milan. As described in Chapter 5, the COST 239 physical topology is utilized as a reference topology for long-haul optical networks, since it provides realistic example in terms of dimension and capacity. For our problem, we utilize a reduced optical network connecting the most relevant

Energy consumption is one of the most challenging aspects to be addressed by the ICT engineering and operation

Furthermore, it is assumed a single fibre per physical link, 40 wavelengths per fibre, and wavelength channels of 10Gb/s each. It is also assumed that each IT node can process up to 2Tb/s, and its power consumption ranges from 6.6 to 13.2KW, under idle and full load, respectively [Cora], while c_{ds} has been assumed to be equal to 1.

An example of the optimal VI topology design for a scenario in which four source nodes that are located in London, Vienna, Copenhagen, and Paris generate demands equal to 50 wavelengths each, is depicted in Figure 32. In this scenario, the generated virtual infrastructure topology consists of seven virtual links and six virtual nodes, while all demands are routed to the IT servers located in Luxembourg. The capacity of each virtual link along with its mapping to the PI is given in Table 2, where it is observed that virtual link Y3 connecting Copenhagen and Luxembourg is realized via physical layer paths u5-u10 and u8-u17-u13, with capacities 25 and 40 wavelengths, respectively.

Figure 33 has been obtained as the result of the analytical resolution of the model with the aforementioned numerical values and methods. The demand generation has been previously described, i.e. randomly selected nodes are utilized to generate demands that are to be served by two IT nodes (i.e. DCs). The performance of the energy-aware VI planning mechanism is evaluated as a function of the average number of demands generated per source.

Table 2: Sample virtual to physical mapping

Virtual link	Capacity (wavelengths)	Physical layer Paths realizing virtual links	Capacity of PI paths (wavelengths)	Average cost / wavelength for virtual link
Y2	50	Path A: u2-u10	15	21,97
		Path B: u3-u11	35	18,97
Y3	65	Path A: u5-u10	25	20,96
		Path B: u8-u17-u13	40	29,69
Y4	15	u5-u6-u7-u15-u21	15	51,86
Y5	15	u14-u23	15	20,83
Y6	40	u22	40	11,25
Y7	40	u16	40	11,62
Y8	70	Path A: u12	40	9,83
		Path B: u15-u14	25	22,01
		Path C: u7-u11	5	18,68

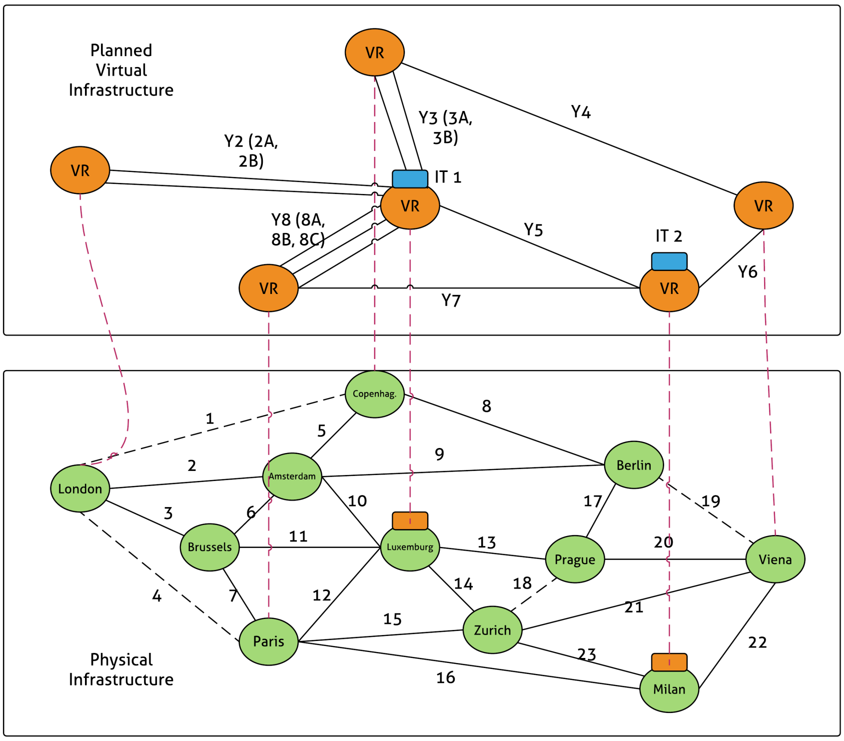

Figure 32: Example of the virtualization of a physical infrastructure

In detail, in Figure 33, the performance of the proposed energy aware VI design is compared to the demand allocation scheme where demands from each source node are assigned to its closest IT server. Note that closest refers to the shortest distance between a source node and a data centre, so the calculation of the allocation for the demands in the VI for this case are performed through simple shortest-path calculation.

Comparing these two schemes, it is observed that the energy aware VI design consumes significantly lower energy for serving the same amount of demands compared to the other scheme in the order of 30%. Basically, in the former approach fewer IT servers are activated to serve the same amount of demands. Given that the power consumption required for the operation of the IT servers is dominant in this type of optical-IT converged networks, switching-off the unused IT resources achieves significant reduction of energy consumption.

In essence, in terms of energy consumption costs, for optical-IT converged networks, and in order to create a single VI, it is still more efficient to set up more lightpaths to route the demands to a single server, rather than serving activating less lightpaths (shortest path) and utilizing several servers. Furthermore, it is observed that in both schemes average power consumption increases almost linearly with the number of demands. However, the relative benefit of the energy-aware design decreases slightly with the number of demands, as we get closer to the full system load.

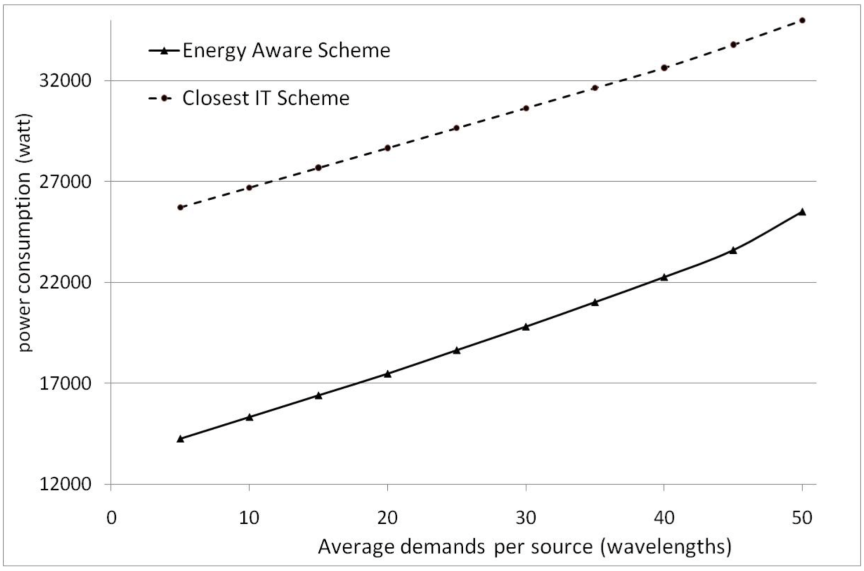

Figure 33: Comparison of the energy aware scheme with the closest IT server demand allocation scheme

6.4 CONCLUSION

Large-scale computer networks supporting both communication and computation are nowadays extensively employed to run distributed high performance applications and services, e.g. Cloud-bases services. These applications require specific IT resources, such as computing or data repositories, interconnected through high capacity, high performance, and high flexibility networks, which cannot be intrinsically delivered by the current best effort Internet. Optical networks, which offer abundant capacity, carrier-grade attributes, and long reach transmission capabilities are one of the most solid candidates to overcome such necessities.

At the same time, energy consumption is one of the most challenging aspects to be addressed by the ICT engineering and operation. In this context, the contribution bases the analysis in the allocation of IT processing jobs in an energy-aware manner through a relatively low energy consumption optical network.

We demonstrate that for a single VI generation, the energy consumption could be reduced in the order of 30% by means of the energy aware VI design process in comparison to a closest distance strategy. Basically, the approach is focused on having fewer number of active IT nodes due to the dominant profile of the IT nodes in terms of energy consumption with regards of the optical networks.

7 CONVERGED VIRTUAL INFRASTRUCTURES

Ewig jung ist nur die Phantasie,
Was sich nie und nirgends hat begeben,
Das allein veraltet nie!
Ode an die Freude - (FRIEDRICH SCHILLER)[a]

Mobile computation offloading has been identified as a key-enabling technology to overcome the inherent processing power and storage constraints of mobile end devices. To satisfy the low-latency requirements of content-rich mobile applications, existing mobile cloud computing solutions allow mobile devices to access the required resources by accessing a nearby resource-rich cloudlet, suffering increased capital and operational expenditures. To address this issue, this chapter proposes an infrastructure approach based on the orchestrated planning and operation of optical DC networks and wireless access networks.

Cloud computing services are becoming available to mobile users, introducing the concept of MCC

Recently, cloud computing services are also becoming available to mobile users, introducing the concept of Mobile Cloud Computing (MCC), where computing power and data storage are moving away from mobile devices to remote computing resources [ATS13]. Although mobile devices have memory, processing power, and storage constraints that could prevent them from acting as media consumption devices, cloud computing services such as Netflix[b], YouTube[c], Pandora[d], and Spotify[e] can assist mobile devices to overcome their inherent hardware limitations [Cis12]. On the other hand, as discussed in [Mun], due to the natural limitations and special characteristics of wireless networks and devices, "the offloading of this type of applications in the cloud requires special considerations in the network design and application deployment."

In order to solve those issues in network design and application deployment, there is the Cloudlet approach [SCH+14]. A cloudlet is a mobility-enhanced small-scale cloud DC that is located at the edge

a Oda a l'Alegria: Només la fantasia es manté sempre jove; el que no ha succeït mai no envelleix
b http://www.netflix.com
c http://www.youtube.com
d http://www.pandora.com
e http://spotify.org

of the network, close to the access segment. The main purpose of the Cloudlet is to support resource-intensive and interactive mobile applications by means of providing computing resources to mobile devices with lower latency. In essence, the Cloudlet approach is based on the deployment of micro-DCs at the edge of the network.

However, there is no solution currently which concentrates on the holistic view of a cloud infrastructure addressing seamless connectivity, latency, mobility, and elasticity challenges [SAGB14]. At the same time, the lack of service differentiation mechanisms for mobile and fixed cloud traffic across the various network segments involved, the fact that they do not consider the varying degrees of latency at each technology domain, and the lack of global optimization tools in the infrastructure management and service provisioning may lead to sub-optimal operation of the converged cloud computing infrastructures.

There is no solution which concentrates on the holistic view of a cloud infrastructure

In this contribution the reader will find a novel multi-objective VI planning scheme [Hou14, HGL+13, WID+13] that takes a holistic approach considering jointly the mobile devices as well as the network and IT segments to ensure allocation of the required resources across all domains. The work here takes into account the impact of the end-to-end delay on the traffic offloading decisions of the mobile devices. It is based on the CONTENT architecture, as depicted within Appendix A - Figure 64. Its objective is twofold: (i) to optimize the performance of VIs in terms of power consumption by identifying the least-energy-consuming VIs and (ii) to prolong the battery lifetime of the mobile devices by identifying whether computational-intensive mobile applications requiring significant amounts of energy should be offloaded to the cloud or not. This approach enables the support of service requests and their specific characteristics such as low latency, QoSs differentiation, and mobility of end users and facilitates globally optimized solutions in terms of objectives such as energy consumption and resource allocation.

7.1 PROBLEM DESCRIPTION

In this section, a modeling framework suitable for planning VIs over an integrated converged infrastructure comprising a cellular LTE system for the wireless access part and an optical metro network that interconnects the end users with the computing resources is presented. Figure 34 depicts the overview of that problem.

The physical infrastructure considered in this contribution was the physical infrastructure related to the CONTENT project, as described in Appendix A. Therefore, the heterogeneous physical infrastructure comprises a wireless access network domain, i.e. LTE, and an optical metro domain interconnecting geographically distributed DCs. The optical metro network is based on the TSON technology supporting frame-based, sub-wavelength switching granularity - refer to Chapter

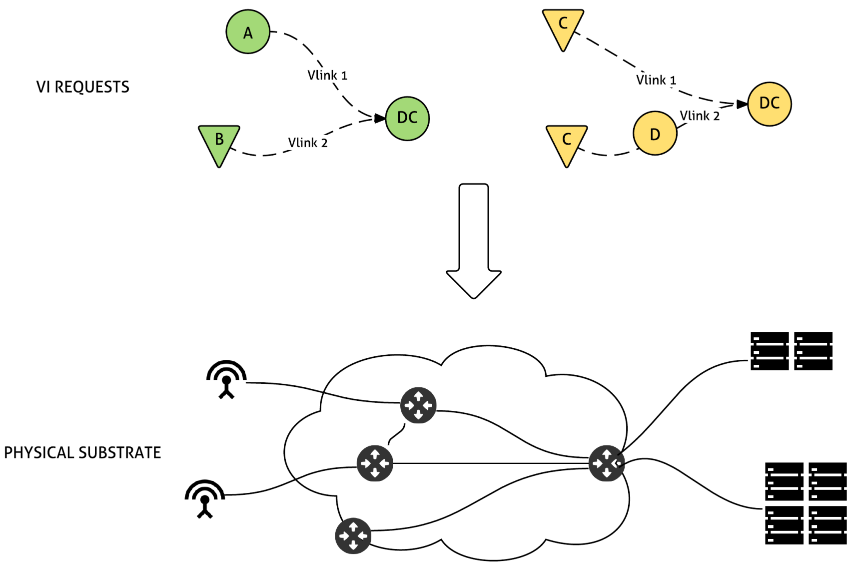

Figure 34: Overview of the general VI planning problem over an integrated converged infrastructure

2. TSON offers connectivity to the wireless access and DC domains by means of providing flexible rates and a virtualization-friendly transport technology. The wireless access segment comprises 4G (LTE) access technology network.

The proposed approach considers a network that is composed of one resource layer, i.e., the PI, and will produce as an output a virtual layer comprising a set Γ of I VIs $\Gamma = (1, ..., I)$. The PI is represented as a weighted graph $G^p = (N^p, \epsilon^p)$ where N^p is the set of PI nodes and ϵ^p is the set of PI links. At the same time, D_i is used to describe the set of demands. These demands belong to the service class set ζ of C services $\zeta = (1, 2, ..., C)$ and need to be served by a set of χ of S geographically distributed DCs $\chi = (1, 2, ..., S)$.

Each service class is associated with certain user groups, i.e. fixed or mobile, that require differentiated quality of service. For example, traffic demands corresponding to fixed cloud applications originate at the TSON edge nodes in the wired domain and need to be served by specific computing resources. A common characteristic of fixed cloud services is that due to the large amount of data that they generate they require very high level of network and computing resources. Mobile traffic on the other hand is generated at the wireless access domain and, compared to the fixed cloud services, requires lower levels of network and computing resources. However, its main disadvantage is that in some cases it needs to traverse several hops before it reaches the IT resources through the optical metro network leading to increased end-to-end delays.

The overall system architecture is illustrated in Figure 35, where in the physical layer the TSON solution has been adapted to interconnect the DCs with the fixed and mobile users. It is based on the CONTENT physical infrastructure substrate, refer to Appendix A. The proposed VI provisioning scheme aims at identifying the topology and determine the virtual resources required to implement a dynamically reconfigurable VI based on wireless optical network and IT resources. Figure 35 depicts an example of two VIs with two different demands each one. For VI one (in red), it can be observed it contains two services of the same class: mobile, i.e. the demand is originated at the wireless access domain, at the eNodeB. However, in the second request (in blue), it can be visualized that there are two different demands, one for fixed service, originated at the metro domain in a TSON node (i.e. demand e), and one for mobile service, coming from the wireless domain (i.e. demand d). It is worth to clarify at this stage that since the contribution deals with the VI provisioning scheme at the same time it tries to maintain the end-to-end delay within determined thresholds, we have utilized a multi-queuing model model for the infrastructure in order to estimate the total delay introduced for the different sub-systems. The queuing model and one example is later detailed and illustrated in Figure 36.

The overall system architecture is based on the CONTENT physical infrastructure

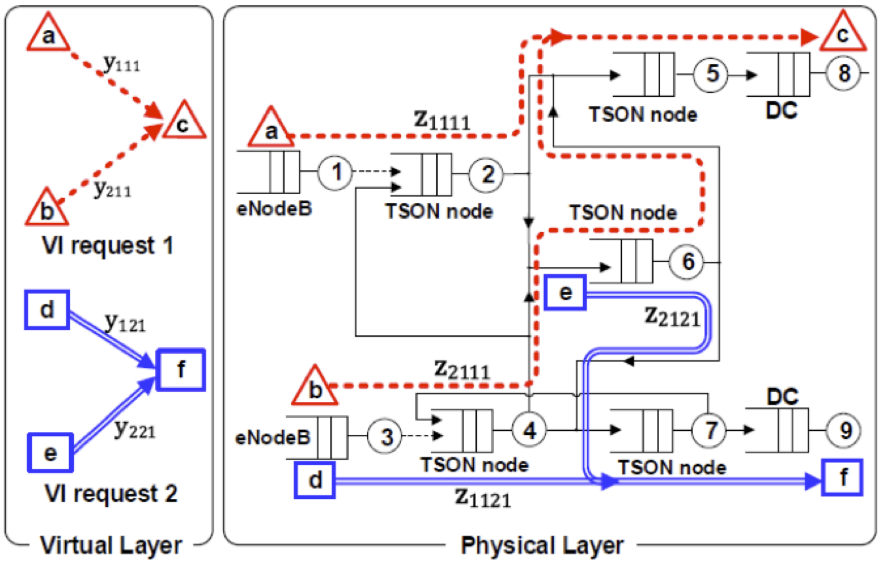

Figure 35: Mapping of the VI requests onto the multi-queuing model of the converged wireless, optical, and DC infrastructures

The multi-objective problem is formulated using Non-linear Programming (NLP), due to the non-linearity of the end-to-end delay. As already mentioned, its primary is to optimize the performance of VIs in terms of power consumption, while its secondary objective is to optimize the performance of the mobile devices in terms of battery lifetime by means of optimally offloading computational intensive mobile applications that require significant amounts of energy to the cloud. The contribution described in this chapter focuses on its primary objectives. Computation offloading for saving battery purposes is not addressed as direct part of the dissertation activities.

For the primary problem, as the major part of the dissertation contribution within this chapter, a set of nodes both in the optical and in the wireless domain is considered to generate demands that need to be served by a set of DCs. These demands apart from computing resources need to be also supported by specific network resources, e.g., number of lightpaths assigned to the corresponding VI paths, time frame during which these demands will be served. In this formulation, it is assumed that the granularity of optical network demands is a portion of wavelength (e.g., $\lambda/100$), while in the wireless domain, the granularity is assumed to be 1 Mbps. As already mentioned, the identification of the suitable DC resources is part of the optimization output.

To formulate this requirement, the binary variable a_{dsic} is introduced, defined as:

$$a_{dsic} = \begin{cases} 1, & \text{demand } d \text{ of } VI_i \text{ belonging to class } c \text{ is assigned to } s \\ 0, & \text{otherwise} \end{cases}$$

whereby c is the service class. It should be also noted that each demand can be served by only one single DC. Now, let h_{dic} be the volume of demand d of service class c belonging to the VI_i, P_{dsic} be a set containing all the possible paths that can be used in order to transfer the traffic volume h_{dic} to the IT server s, and x_{dpic} be the flow realizing demand d on path $p \in P_{dsic}$. Then, the following demand constraints should be satisfied in the VI:

$$\sum_{s} \sum_{p} a_{dsic} x_{dpic} = h_{dic}, d \in D_i, i \in \Gamma, c \in \zeta \tag{22}$$

Summing up the paths through each link $e(e \in E_i^{\nu})$ of the VI_i, the necessary virtual capacity y_{eic} of link e that can support all demands belonging to service class c is given by the following expression:

$$\sum_{d} \sum_{p} \delta_{edpic} x_{dpic} \leqslant y_{eic}, e \in E_i^{\nu}, i \in \Gamma, c \in \zeta \tag{23}$$

where δ_{edpic} is a binary coefficient taking the value equal to 1 if link e of VI_i belongs to path p realizing demand d of service class c at server s, 0 otherwise.

Once the capacities in the virtual layer have been determined, the necessary resources in the physical layer need to be identified [Sch12]. To achieve this, the virtual capacities y_{eic} are treated as demands that need to be supported by specific PI resources. Assuming that $q(q \in$

Q_{eic}) is the PI's candidate path list realizing virtual link capacity y_{eic}, the following VI demand constraints should be satisfied

$$\sum_{q} z_{eqic} \leqslant y_{eic}, e \in E_i^{\nu}, i \in \Gamma, c \in \zeta \tag{24}$$

In equation 24 the summation is taken over all paths q on the routing list Q_{eic} of link e and z_{eqic} is the flow on path q realizing virtual link e of VI_i and service class c. Furthermore, during the mapping process from the VI to PI, the PI link capacity constraints must be also satisfied. To achieve this, initially the binary coefficient γ_{geqic} is introduced and defined as follows:

$$\gamma_{geqic} = \begin{cases} 1, & \text{if link g belongs to path qrealizing vlink } e \in VI_i \text{ and serv. class c} \\ 0, & \text{otherwise} \end{cases}$$

Then, the capacity u_{gic} that is required by each PI link g to support the demands of VI_i that belong to service class c is described through the following linear expression:

$$\sum_{e} \sum_{q} \gamma_{geqic} z_{eqic} \leqslant u_{gic}, g \in E^p, i \in \Gamma, c \in \zeta \tag{25}$$

At the same time, the total load at each link g should not exceed its total capacity, Υ_g:

$$\sum_{i} \sum_{c} u_{gic} \leqslant \Upsilon_g, g \in E^p \tag{26}$$

Apart from the network capacity constraints, defined in 23, 24, 25, and 26, the requested processing power (measured in Million Instructions Per Second (MIPS)) at each server s should not exceed its capacity Φ_s:

$$\sum_{i} \sum_{d} \sum_{p} \sum_{c} a_{dsic} M_{dsc}(x_{dpic}) \leqslant \Phi_s, s \in S \tag{27}$$

Note that in 26 the summation is taken over all demands that arrive at server s. M_{dsc} is a parameter known as network to compute ratio specifying the computational requirements for demand d that belongs to service class c on server s. This parameter in various services are quantified in [CLB+12].

So far, the proposed scheme ensures that there are sufficient network and processing capacities to support the requested services. Apart from network bandwidth requirements, end-to-end delay guarantees should also be provided. However, given that in highly loaded networks queuing delay is the dominant part of the end-to-end delay, the virtual infrastructure control layer needs to be also capable of making queuing and scheduling decisions across all the technology domains involved. A typical queuing decision example includes the reservation of a specific portion of the receivers'/transmitters' queues by a VI either at a TSON edge node or at an eNodeB, with the objective to maintain the end-to-end delay below a predefined threshold. Figure 36 shows the example on the queuing system of a converged wireless access and optical metro network.

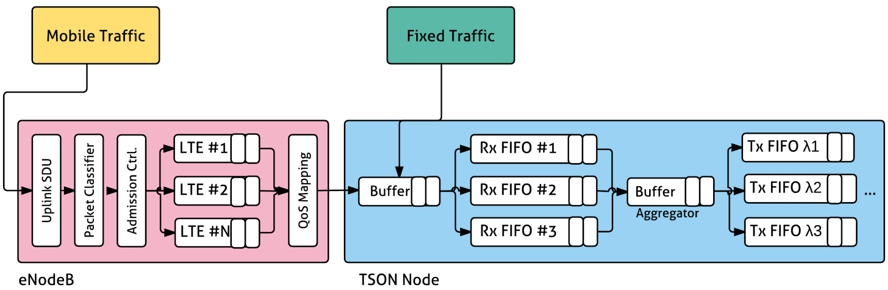

Figure 36: Multi-queuing model for the converged wireless-optical network infrastructure

Basically, in order to consider end-to-end delay guarantees for the different VIs, it is not sufficient to reserve in advance bandwidth requirements. The control layer operating the virtual infrastructure needs to be capable of configuration of the queuing systems within each device so that delays are sufficiently guaranteed.

In order to mathematically formulate this issue, the PI is modeled as an open queuing network, in which each node $n \in N^p$ consists of m_n identical service modules[f] with service rates u_n. The schematic view is depicted in Figure 36. Assuming that the conditions of the BCMP theorem [BCMP75] are satisfied and both the arrival and service rates are load-independent, a closed form approximation for the end-to-end delay for the services that are provided by each VI can be extracted based on the following steps:

1. First, the arrival rate, λ_{nic}, for the class c demands of VI_i at the nth node of the PI is determined by

$$\lambda_{nic} = \sum_{g} b_{gin} u_{gic}, n \in N^p, i \in \Gamma, c \in \zeta \tag{28}$$

where b_{gin} is binary coefficient taking values equal to 1 if link g is used by VI_i is terminated at node n; 0 otherwise (see

f In the wireless access domain, m_n corresponds to the number of input queues at an eNodeB, while in the optical domain, it corresponds to the number of receiver/-transmitter queues in the TSON edge

Figure 35). Once λ_{nic} has been determined, the relative arrival rate, also known as visit ratio) of a demand of the cth class of VI_i is at the nth node, defined as e_{nic} is estimated by $e_{nic} = \lambda_{nic} / \sum_d h_{dic}$[g].

2. Then, the utilization p_{nic} at the nth node of the PI with respect to the service class c is estimated through:

$$p_{nic} = \lambda / m_{nic} u_n$$

where m_{nic} is the number of the service modules in the PI node n that are leased by the VI_i to serve class c demands.

3. In the next step, the steady-state probability at each node n is calculated using the well-known formula for $M/M/m$ systems. It is only considered steady-state since the problem is about VI planning, and it is assumed that the provisioned VIs will be operated efficiently in the long term. There is no aim at studying the short term performance.

A closed form approximation for the end-to-end delay for the services provided by the VI can be extracted

$$\pi_{nic}(k_{nic}) = \begin{cases} \pi_{nic}(0)\frac{(m_{nic}p_{nic})^{k_{nic}}}{k_{nic}!} & , 0 \leqslant k_{nic} \leqslant m_{nic} \\ \pi_{nic}(0)\frac{p_{nic}^{k_i} m_{nic}^{m_{nic}}}{m_{nic}!} & , k_{nic} \geqslant m_{nic} \end{cases} \tag{29}$$

where k_{nic} is the number of VI_i demands of class c at the node n. $\pi_{nic}(0)$ is given by:

$$\pi_{nic}(0) = \left[\sum_{k_{nic}=0}^{m_{nic}-1} \frac{(m_{nic}p_{nic})^k_{nic}}{k_{ni}!} + \frac{(m_{nic}p_{nic})^{m_{nic}}}{m_{nic}!(1-p_{nic})} \right]^{-1} \tag{30}$$

Then using 29, and 30, the steady-state probability of the converged infrastructure assigned to VI_i can be calculated as the product of the state probabilities of the individual nodes, that is

$$\pi_{ic}(k_{1ic}, k_{2ic}, ..., k_{nic}) = \prod_n \pi_{nic}(k_{nic}) \tag{31}$$

4. In the subsequent step, after applying Little's theorem, the mean response time, $T_{inc}(m_{nic}, \lambda_{nic})$, of a VI_i demand of the cth class at the nth node is evaluated

g It is assumed that all demands are served

5. Then, in order to bound the end-to-end cloud delay of each service class c below a specific threshold, L_c, the following constraints should be satisfied

$$\sum_{n} \varepsilon_{inc} T_{inc}(m_{nic}, \lambda_{nic}) \leqslant L_c, i \in \Gamma, c \in \zeta \tag{32}$$

   where ε_{inc} is a binary variable taking value equal to 1 if node n in the PI is used by the VI_i to service class c traffic.

Recall that the total number of modules that will be leased by each VI_i should not exceed the capacity of the nodes:

$$\sum_{i} \sum_{c} m_{nic} \leqslant m_n, n \in N^p \tag{33}$$

As already mentioned, the primary objective of the proposed scheme is to optimize the performance of the planned VIs in terms of power consumption. Given that the total power consumption depends on:

1. k_{dpic} that is the routing cost for the demand d that belongs to service class c of VI_i allocated to path p and reflects the energy consumed by each path. For further details regarding the power consumption model adopted in this study, the reader is referred to [KT11].

2. P_s that is the total power consumed at a DC s when a percentage of ν_s% of its resources are utilized and it is defined through the following linear equation [Dav]:

$$p_s(\nu_s) = P_s^i + P_s^b \nu_s \tag{34}$$

   whereby P_s^i and P_s^b denote the power consumption of the DC s at the idle state and per utilization unit, respectively. The power consumption model for the IT resources is the same as in previous Chapter 6. The following expected cost function should be minimized:

$$\min \sum_{dpic} k_{dpic} x_{dpic} + \sum_{s} P_s(\nu_s) \tag{35}$$

   subject to constraints 22, 23 , 24 ,25, 26, 27, 28, 29, 30, 31, and 32. Note that the first term of 35 accounts for the total power consumption of the network domain, while the second tries to minimize the power consumed by the DCs. At this point, it should be mentioned that the total optical network power consumption is determined by the power consumption of the individual OXCs and fibre links comprising the optical network. It is the same model as the one expressed in previous Chapter 6.

In addition to power consumption due to active devices in the power estimation model, we incorporate 100 % power overhead due to cooling [KT11]. Note that all power consumption calculations account only for the transport equipment of the optical network and that the power dissipated by electronic circuits, such as control boards of OXCs or hardware implementing protocol functionality, is not considered. For more detailed information regarding the energy consumption figures and the formulas describing the power consumption models of the OXCs, the reader is referred to [KT11].

The VI planning scheme described through 35 aims at minimizing the total power consumption of the converged wireless, optical DC network. However, for traffic demands that are generated in the wireless domain, computation offloading is beneficial for the mobile device if the total energy that is consumed in the mobile terminal for transmitting and receiving data to the DC is at least equal to the total energy that is consumed for data processing in the mobile device itself [KL10]. Let p_m^p (watt) be the power that is consumed in a mobile device for data processing, p_m^i (watt) while being in idle mode, and p_m^t (watt) during the phase of data transmission/reception. Note that the modules that are responsible for data transmission/reception consume much higher energy compared to the modules that are responsible for data processing [CH10], even for the case where computational-intensive applications are processed [APTM13]. Hence, the power consumption of the mobile device during the transmission, processing, and the idle phase follows the following inequality [TKS+12]:

$$p_m^t > p_m^p > p_m^i \tag{36}$$

Furthermore, if a traffic demand with volume h_{dic} is processed locally by mobile processor with speed S_M, the energy consumed is $h_{dic}p_m^p/S_M$. However, if the same traffic demand is offloaded to the VI_i, the energy consumption in the mobile devices is $p_m^t T_{iW} + p_m^i(T_{iO} + T_{iDC})$, where T_i, T_{iO}, and T_{iDC} are the delays that are introduced in the wireless, optical, and DC segments of the VI_i, respectively. Basically, when offloading traffic, the power consumption at the mobile device can be calculated by the cost of transmiting in the wireless access domain $p_m^t T_{iW}$, plus the cost while it is waiting for the data to be processed in the DC, i.e. $p_m^i(T_{iO} + T_{iDC})$.

Hence, in the secondary optimization problem, each mobile device has to identify its optimal offloading strategy, captured by the binary variable ν_m, where $\nu_m = 0$ when data is processed locally, 1 otherwise, in order to minimize the following expected cost:

$$\min_{\nu_m}(1-\nu_m)\frac{h_{dic}p_m^p}{S_M}+\nu_m\left[p_m^t T_{iw}+p_m^i(T_{iO}+T_{iDC})\right], \nu_m \in 0,1 \quad (37)$$

The multi-objective optimization problem described above has been solved using the ϵ-constraint method [Eic08]. This involves the minimization of the primary objective function, while the secondary objective has been written in the form of an inequality constraint. For the non-linearity of the end-to-end delay constraint, relaxation techniques have been utilized [Ber99], which in essence transfer the delay constraint to the objective function and replace it by a simpler linear constraint. The resolution of the problem has been performed with a custom-made optimization framework, developed within Matlab[h] by one of the co-authors in [ATR+15].

7.2 NUMERICAL RESULTS

The performance of the proposed VI planning scheme across the multiple domains involved is studied based on an infrastructure that is part of GRNET's[i] Athens optical metro network topology. For the PI a macro-cellular network with regular hexagonal cell layout has been considered similar to that presented in [AGG+11], consisting of 12 sites, each with 3 sectors and 10MHz bandwidth, operating at 2.1GHz. The inter-site distance has been set to 500m to capture to scenario of a dense urban network deployment. Furthermore, a 2x2 Multiple Input Multiple Output (MIMO) transmission has been considered, while the users are uniformly distributed over the serviced area. Each site can process up to 115 Mbps, and its power consumption ranges from 885 to 1087 W, under idle and full load, respectively [AGG+11].

For the computing resources, two "Sun Oracle Database Machine Basic Systems" [Cor09] have been considered where each server can process up to 36 Gbps of compressed flash data and their power consumption ranges from 900 to 1800W, under idle and full load, respectively. Furthermore, for the cloudlets, the linear power consumption model presented in 34 has been considered with $p_s^i = 487,5w$ and $p_s^b = 975w$.

Analysis of the numerical results has been performed with actual statistical data from GRNET

The physical TSON topology assumed is illustrated in the right part of Figure 35, where the length of the point-to-point optical links are below 5 km and the supported data rate is 8.68Gbps. The power consumption of the TSON equipment is measured to be 50w for the Erbium Doped Fiber Amplifiers (EDFAs) and 100 mw for the PLZT

h http://es.mathworks.com/products/matlab
i http://mon.grnet.gr/rg/

chip. The mobile devices are equipped with an IntelXScale processor with P_m^t=1.3w, p_m^p=0.9w, and p_m^i=0.3w (see [KL10] for a similar power consumption model). It is also assumed that the mobile devices are uniformly distributed over the served area while the number of mobile devices per sector is equal to 10. Finally, each mobile device is able to process up to 400 MIPS.

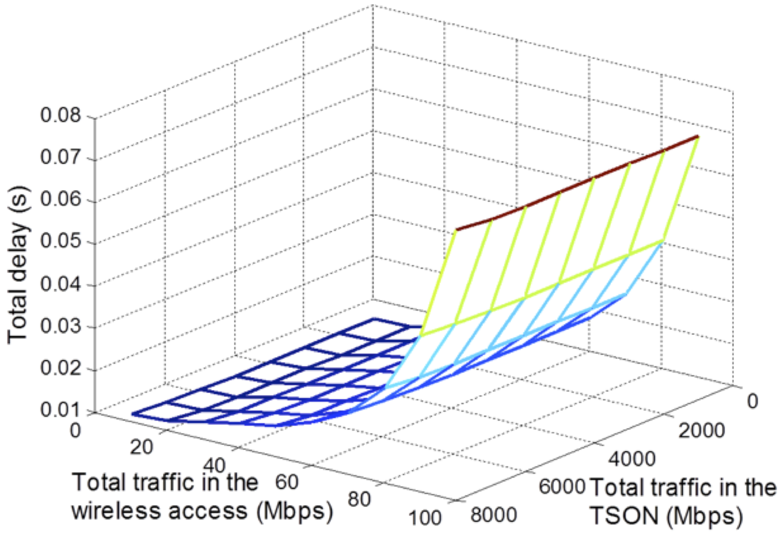

Figure 37: End-to-end delay for a mobile cloud demand with traffic volume 1MB under various background traffic profiles

Initially, the impact of the background network traffic on the total end-to-end delay is analyzed for a scenario where 1MB of data need to be exchanged between the mobile device and an IT server. Delays have been calculated analytically based on the open queuing model described in previous section and actual statistical data from GRNET and different traffic profiles, for both traffic requests and background traffic. The analysis through the analytical calculation is done for different values of the background traffic in both the wireless domain (10 to 100 Mbps) and the TSON metro domain (1000 to 8000 Mbps) calculated through the previous model, considering the aforementioned processing values, i.e. 115 Mbps and 8.68 Gbps respectively. Background traffic is considered to affect the available throughput, and the values can be estimated analytically, as explained in the previous section. For example, in the wireless access, to transmit 1Mb, if there are 50Mbps of background noise, it means that there are only 65Mbps available as throughput, which will provide a delay of 0,015 seconds, plus the delay introduced by the TSON domain until reaching the IT resource.

In Figure 37, it is observed that, due to the scarcity of resources in the wireless access network, the increase in the background load in the wireless domain leads to an exponential increase in the end-to-end delay, which is the most significant item of the proposed model

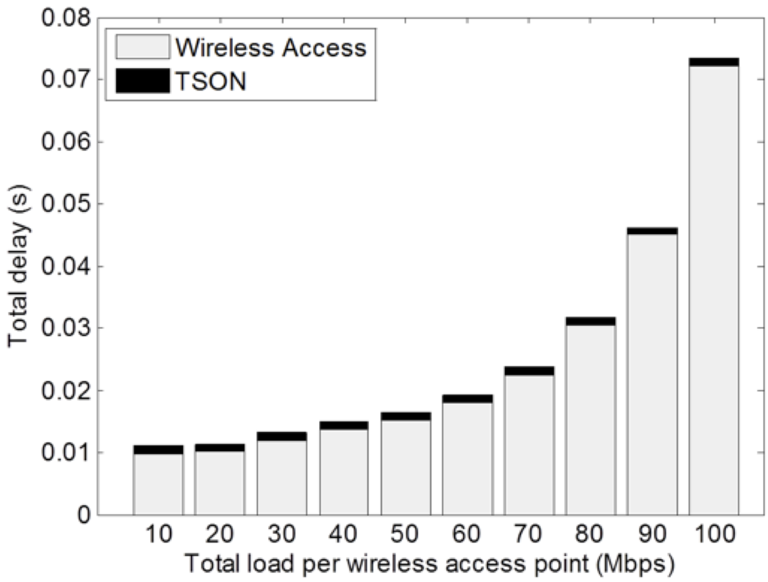

Figure 38: Delays introduced in the various domains of the converged infrastructure as a function of the traffic load in the wireless access network (load in the TSON = 3Gbps)

in this contribution. On the other hand, with the increase in the background traffic in the optical domain, the end-to-end delay remains almost unaltered (the total delay is increased by less than 2 %).

The increase in the background traffic in the wireless domain leads to an exponential increase in the end-to-end delay introduced

Similar results are presented in Figure 38 where the total end-to-end delay when applying the proposed approach is depicted as a function of the background traffic load in the wireless access domain. It is observed again that with the increase in the traffic load in the wireless domain from 10 to 100 Mbps, the end-to-end delay is increased by a factor of 6. At the same time, the optical network is responsible for less than 1.5% of the overall network delay. For this case, the load in the TSON domain has remained constant at a rate of 3Gbps, which introduces a total delay of around 0,0017 seconds, which has a minor impact in the total end-to-end delay compared to the impact produced by the wireless domain.

Figure 39, illustrates the total power consumption of the converged infrastructure (wireless access, optical network, and IT resources) as a function of the latency threshold when applying the proposed and the cloudlet approach. As described below, the problem has been resolved with a custom-built appliance over Matlab for the non-linear formulation. The objective is to minimize the energy consumption of both the network (wireless access plus metro domain) and DCs (refer to 35, at the same time that the end-to-end delay is guaranteed below a given threshold, as expressed in equation 32. As a reminder, it is worth to mention that power consumption models in the network segments have been adopted from [KT11] and for the DCs comes from expression 34.

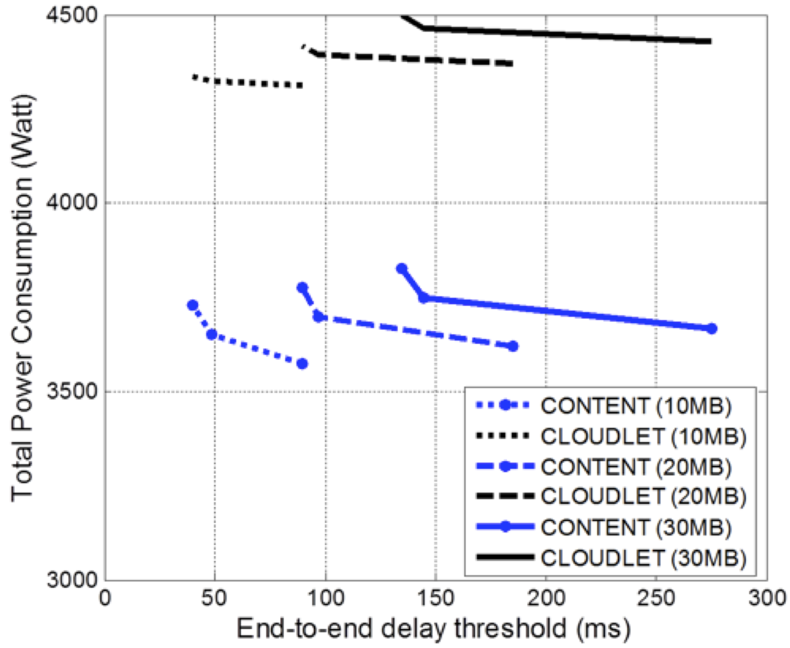

Figure 39: Total power consumption as a function of the delay threshold for various computing platforms and service requests

Regarding the Cloudlet approach utilized for comparison, the same model have been utilized, with the difference that due to the nature of the approach, i.e. to include small-scale, less efficient data centres close to the network edge and the wireless access, we consider that the requests will utilize always the closest data centre. However, the end-to-end delay in this approach will always get rid of the delay introduced by the TSON segment.

In Figure 39 it is observed that the proposed solution (named CONTENT due to project where it was originated) consumes significantly lower energy (corresponding to lower operational cost, i.e. OpEx) to serve the same amount of demands compared to the cloudlet. This is due to that in the former approach, fewer IT servers are activated to serve the same amount of demands. Another interesting observation is that with the increase in the size of data that are exchanged between the end devices and the computing resources (e.g., from 10 to 30 MB), the total power consumption is increased. As expected, with the increase in the service requirements, additional network and computing resources are assigned to the VIs to cover the end users demands.

Finally, the total power consumption is very much dependent on the end-to-end delay constraints. For example, services with strict packet delay constraints (e.g. Priority 3 Guaranteed Bit Rate (GBR) services with 50ms packet delay [3GP]) require high levels of power to operate. However, when this constraints is relaxed (e.g. non-GBR services of Priority 6 with 500ms packet delay) the total power consumption is decreased. In order to satisfy services with strict end-to-end delay constraints, the long waiting times in the queues should be avoided. To achieve this, additional resources need to be assigned to the VIs, leading to increased service rates and increased power consumption.

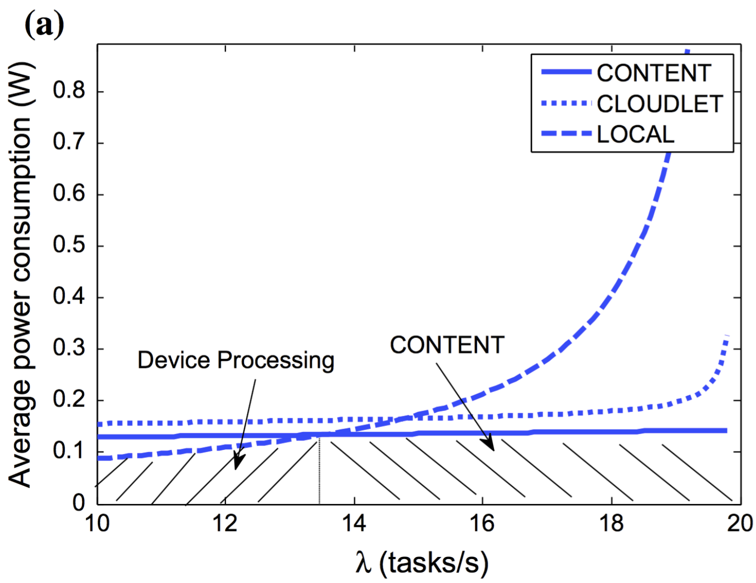

Figure 40: Impact on power consumption of the mobile devices when there is high availability of wireless network resources

So far, the performance analysis of the proposed multi-objective scheme has been limited to the network and DC infrastructure providers. In what follows, emphasis is given to the analysis of the impact of the proposed approach in this contribution on the average consumption and on the end-to-end delay of the mobile devices. The analysis aims at defining the point where is convenient, from the power consumption perspective, for an end-user device to offload some of the computation tasks.

In Figures 40, and 41, the proposed scheme, the cloudlet, and the local (end device) processing approaches are compared in terms of average power consumption for the mobile devices under different task arrival rates. It is worth to mention that the figures only consider the power consumption for the mobile devices as a function of the different tasks that are to be processed. The numerical results are produced assuming that each task requires a processing capacity equal to 20 MIPS, as well as utilizing the model and resolver framework defined in the previous section. Refer to the beginning of the section where it was stated that a mobile device can process a maximum of 400 MIPS, thus a maximum of 20 tasks.

Basically, two major scenarios have been considered: when there is high availability of network resources in the wireless access domain; and, on the other hand, the contrary case, where there is not high availability of resources in the access. The aim of selecting these two scenarios is to analyze also the non-linear effect of the delay introduced in the wireless access.

Figure 40 depicts the case of average power consumption utilizing the proposed scheme, the cloudlet, and the local device in the first scenario, i.e. high availability of network resources. In this case, it is observed that MCC offloading is beneficial for the mobile devices only when a significant amount of tasks need to be processed. In essence, it can be seen that as long as the number of tasks to be computed is over approximately 14 tasks per second, offloading option is the preferred option for the power consumption of the mobile device. It is depicted in the figure as the bottom right region named CONTENT.

In fact, under these operational conditions, the total time that a mobile device will spend in transmission and the idle states will be much shorter than the time required for local processing of the same amount of data ($T_{iw} + T_{iO} + T_{iDC} << h_{dic}/S_M$). Considering that $p_m^i < p_m^p < p_m^t$, the total power consumption for the mobile device will be lower than that of local processing (see bottom right part of Figure 40).

On the other hand, when the average number of tasks that arrive at each device is small (below 13.6 tasks per second), local processing is preferred by the devices in terms of power consumption. In this case, $h_{dic}/S_M < T_{iw} + T_{iO} + T_{iDC}$ and given that $p_m^p < p_m^t$, local processing will be more beneficial than remote data processing.

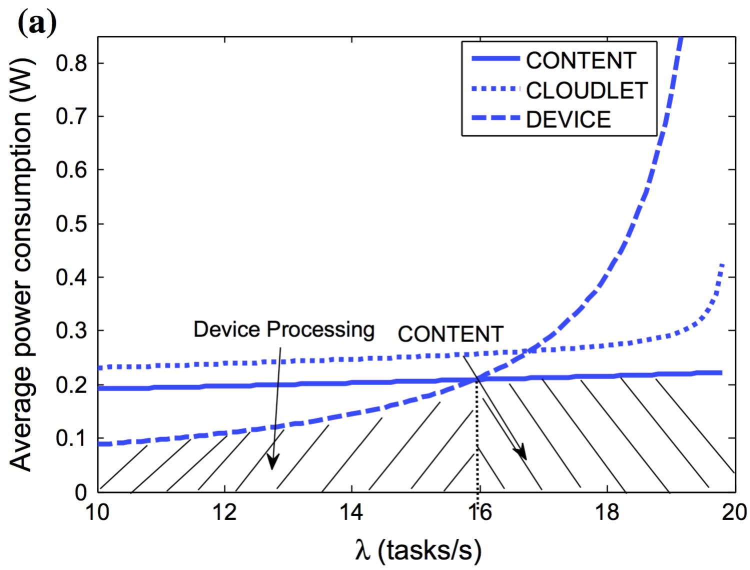

Figure 41: Impact on power consumption of the mobile devices when there is limited availability of wireless network resources

Similar results are provided in Figure 41, where a scenario with limited network resources is considered. In this case, the computation requirements threshold above which offloading benefits the device has been increased. This is direct consequence to the scarcity of resources in the wireless domain, which increases the queuing delays leading to increased communication costs. In its turn, this increases the power consumption of mobile devices since they have to remain in the idle state for longer time periods.

Figure 41 depicts how the threshold for offloading is increased in this scenario up to the value of 16 tasks per second. Basically, this means that in the cases where there is not high availability of wireless access resources, mobile devices will only be offloading computation tasks when they are about to process more than 16 tasks per second, i.e. more than 80% of their maximum computing capacity.

7.3 CONCLUSION

This contribution focused on a next generation ubiquitous converged network infrastructure model based on the IaaS paradigm. It aims providing a technology platform interconnecting geographically distributed computational resources that can support a variety of Cloud and mobile Cloud services. The concept of virtualization across the technology domains is adopted as a key enabling technology to support such a vision.

A novel multi-objective virtual infrastructure provisioning scheme over converged wireless, optical network, and computing resources has been presented in order to a) minimize the energy consumption of the converged infrastructures; and b) to maximize the lifetime of mobile devices, by means of analyzing the optimal decision point in order to offload computational tasks.

Numerical results indicate that there are a number of trade-offs relating to end-to-end service delay, resource requirements and energy consumption levels of the infrastructure across the various technology domains closely associated with the service characteristics.

Part III

PROPOSAL

All of old. Nothing else ever. Ever tried. Ever failed.
No matter. Try again. Fail again. Fail better.
- SAMUEL BECKETT (Worstward Ho)

PREFACE

The last part of the doctorate comprehends the most difficult part to achieve. Following a quick search, research *"comprises creative work undertaken on a systematic basis in order to increase the stock of knowledge, including knowledge of humans, culture and society, and the use of this stock of knowledge to devise new applications"*. It is used to establish or confirm facts, reaffirm the results of previous work, solve new or existing problems, support theorems, or develop new theories [OEC02][j].

In fact, taking a look at the etymology of the word research, it is derived from the Middle French *"recherche"*, which means indeed to go seeking, the term itself being derived from the Old French term *"recerchier"* a compound word from "re" + "cerhier", or "sercher", meaning to search.

Obviously, several definitions on the term research have been made. Shuttleworth mentions *"in the broadest sense of the word, the definition of research includes any gathering of data, information and facts for the advancement of knowledge"* [Shu08]. Creswell in [Cre08] states *"research is a process of steps used to collect and analyze information to increase our understanding of a topic or issue. It consists of three steps: Pose a question, collect data to answer the question, and present an answer to the question"*.

More than one hundred similar definitions could be found in the literature. The remarkable points are that the first and second parts of the doctorate are research because they comprehend *work undertaken on a systematic basis in order to increase the stock of knowledge*, this last part comprehends the *creative work undertaken on a systematic basis in order to use the stock of knowledge to devise new applications*.

In this sense, this part contains two major proposals. First of all, the dynamic re-planning of already provisioned virtual infrastructures. Basically, information regarding the volume and type of service requests is not precisely available in advance of the requests to the VI providers. Cloud services can scale up and down on demand. Therefore, that dynamic adaptation of the infrastructure to the elasticity of the Cloud services requires constant changes. This proposal provides a complete analysis, together with a distributed enterprise information system, running on top of a virtual infrastructure, and how a a function of the load in the system, the re-planning mechanisms could be triggered in order to adapt the virtual infrastructure to the service requirements.

Finally, the second proposal made falls within the creative work undertaken umbrella. NFV aims at decoupling the network functions from the actual hardware where they are executed. Thus, most of the

j Definition partially extracted from `http://en.wikipedia.org/wiki/Research` network functions will run on standard virtualized servers by means of software, which is expected to significantly reduce capital expenditures, while at the same time the software automation reduces operational expenditures.

Several challenges emerge in order to achieve such objective. We identified one of this novel challenges as scheduling the functions over the standard servers in order to minimize the total execution time of the different workflows or network services, considering a NS is composed of different virtual network functions. The last proposal presents a model to solve this precise challenge associated to the virtual network function management and orchestration. The work includes a heuristic to solve the problem, which is a variation of a greedy approach that in each iteration schedules a network function that minimizes the overall time assuming that the remaining network functions are scheduled on the earliest finishing servers.

8 DYNAMIC RE-PLANNING OF CONVERGENT VIRTUAL INFRASTRUCTURES

No man ever steps in the same river twice,
for it's not the same river and he's not the same man.
- HERACLITUS

The migration towards a full range and large-scale convergence of Cloud and network services has become the current trend

Cloud computing service emerged as an essential component of the Enterprise IT infrastructure. Migration towards a full range and large-scale convergence of Cloud and network services has become the current trend for addressing requirements of the Cloud-enabled environment, as stated in Chapter 1. The approach adopted takes the infrastructure as a service paradigm to build converged VIs, which allow offering tailored performance and enable multi-tenancy over a common physical infrastructure. Thanks to virtualization, new exploitation activities of the PIs may arise for both transport networks and DCs services. The approach presented in this chapter makes network and DCs' resources dedicated to cloud computing to converge on the same flexible and scalable level. It is based on the automation of the virtual infrastructure provisioning service. On top of the VIs, a coordinated operation and control of the different resources is performed with the objective of automatically tailoring connectivity services to the cloud service dynamics.

Furthermore, in order to support elasticity of the cloud services through the optical network, dynamic re-planning features have been provided to the virtual infrastructure service, which allows scaling up or down existing virtual infrastructures to optimize resource utilization and dynamically adapt to users' demands. In this sense, the dynamic re-planning of the VI service becomes a key component for the coordination of Cloud and optical network resource in an optimal way in terms of resource utilization. An example of distributed enterprise information system is presented as a real use case for such a dynamic VI service, which scales up and down the infrastructure as a function of the application requests.

8.1 INTRODUCTION

Cloud computing services are one of the fastest growing business opportunities for Internet service providers and telecom operators [Ver11]. The emergence of even more resource demanding services, which hold high-performance, high-capacity, network- based applications with strict IT (e.g. computing and data repositories) resource requirements are driven by many technological advances. Distributed computing systems and large-scale computer networks supporting both communication and computation are able to run distributed high-performance applications. However, these applications require specific Cloud services that involve distributed IT resources interconnected through high-capacity, high-performance, and flexible networks, which cannot be intrinsically delivered by the current best-effort Internet [VBFC+11]. In response to these needs, optical networking offers very high-capacity transport with increased dynamism and flexibility through recent control planes, resource virtualization and elastic mechanisms.

Converged virtualization in multi-tenant environments allows the usage optimization of the hardware devices

As stated in Chapter 1, the migration towards a full range and large-scale convergence of Cloud and network services has become the current trend, which implies the extension of the virtualization concept from only computing to a joint computing and networks consideration. In fact, resource virtualization is envisaged as the process that will homogenize both Cloud and network resources through the provisioning of combined IT and network VIs. Converged virtualization in multi-tenant environments allows the usage optimization of the hardware devices, and therefore it actually avoids having an infrastructure with many similar devices performing much less than 100% just because they have to be under different administrative domains [TAG+11b].

In this context, and mentioned in Chapter A the GEYSERS European project proposed the interconnection of IT resources through WSON networks in a converged infrastructure that can support delivery of end-to-end services through joint provisioning of Optical Network + IT resources at the edges. The project adopted the concept of the IaaS facilitated through virtualization of the combined DC and network infrastructure in order to offer performance advantages and enable sharing of physical resources, which brings new exploitation opportunities for the underlying physical infrastructures, both transport network and Data Centres.

Considering the layered architecture described previously in Figure 60, convergence and coordination of cloud computing and network resources in the proposed architecture takes place at the virtual infrastructure planning and operation stages respectively. By means of decoupling the traditional infrastructure from the service provided on top of it, the architecture facilitates the appearance of new challenges on how to dynamically and optimally match the actual infrastructure with the service provided on top of them and avoid over-provisioning of resources. The proposed architecture introduces a new dynamism where ownership and operation of infrastructures are split and assumed by different players through the provisioning of virtual infrastructures as a service, allowing new actors to enter the market in a relatively short time and be capable of generating revenues with low initial investments.

Network virtualization is recognized as an enabling technology for the future Internet. Through dynamic mapping of virtual resources onto physical hardware, the benefit from the existing hardware can be maximized. Optimal dynamic resource allocation mechanisms, leading to the self-configuration and organization of future networks, will be necessary in order to provide customized services to the end-users. However, several challenges emerge on the arena derived from the virtualization environments.

Dynamic mapping of virtual resources onto physical hardware maximizes the benefit extracted from existing hardware

8.2 VIRTUAL INFRASTRUCTURES AS A SERVICE

One of the key components of any on-demand cloud provisioning system is the Service Delivery Framework (SDF) [TR112], initially proposed by the TeleManagement Forum. We extend this conceptual framework connecting it to the proposed architecture and applying it to the dynamic and automated provisioning system. Therefore, a virtual infrastructure is considered and provisioned as a service, with its own lifecycle. In detail, virtual infrastructures are de-materialized resource aggregates, which provide a service over a time-limited period. Their lifecycle, as shown in Figure 42, involves their planning and creation phases, the service delivery phase, and finally their decommissioning.

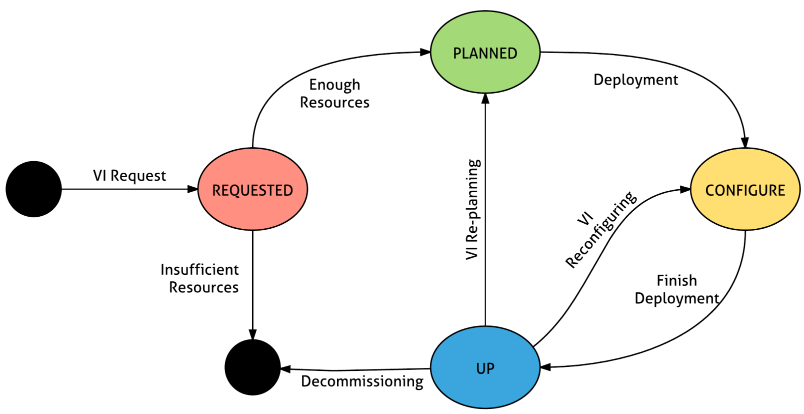

Figure 42: Virtual Infrastructure Lifecycle

In the considered layered architecture, as proposed by GEYSERS and depicted in Appendix A, VIs are requested from the virtual infrastructure operator, through the Service Middleware Layer (SML). Each request contains the description of the resources requested within the VI, the topology describing how they should be connected, and the associated lifetime. When the operator requests a converged VI with both IT and network resources, the request is received at the internal virtualization layer allocator through the VI service interface. The algorithms utilized for planning the VI are explained later in this chapter. The state of a virtual infrastructure always depends on the different states of the virtual resources that compose it. Hence only once all resources of the virtual infrastructure could have been allocated, the VI moves to the planned state (PLANNED in Figure 42), otherwise the request is rejected.

Once the VI is planned, its different virtual resources are created with the different parameters given in the VI request, and if the creation is successful, it moves to the configured state (CONFIGURE in Figure 42). The virtual infrastructure becomes up once all of its virtual resources have been instantiated on the physical resources to which they had been assigned (UP in Figure 42). It is then ready to be handed over to the users (i.e. virtual network operators), who can proceed with operating the network resources, installing applications or even create new virtual nodes. At the end of the reserved lifetime of a virtual infrastructure, all its virtual resources are decommissioned.

8.2.1 *VI service provisioning challenges*

When providing virtual infrastructures composed of both IT and network resources as a service, the first problem in the management is the parameterization of the virtual infrastructure itself; i.e. the description of all the involved resources and their interconnections. Furthermore, virtual infrastructures need to be appropriately designed and operated to address the very dynamic and unpredictable traffic profiles and service characteristics they are supposed to support. As an example, underestimating the required network and IT resources may lead to an inability to satisfy end-users requirements, whereas an overestimation may lead to over-provisioning of resources and hence increased operational and capital expenditures (OpEx and CapEx). In this context, optimal VI planning with respect to specific objectives of interest plays a key role in order to enable the IaaS paradigm into our proposal. Virtualization, and, in detail, virtual network planning into the physical infrastructure is a well-studied topic in the literature [CB09, FBTB+13, PPSJ12, CB10].

Given that the volume and type of service requests is not precisely known in advance, the required virtual infrastructure capacity may need to scale up and down on demand to ensure that all service requests can be supported in an efficient manner. This in practice can be performed through **dynamic VI re-planning**. Although the VI planning and re-planning algorithms are realized in the LICL component of the layered architecture, the triggering for the planning process comes from the upper layers.

An issue of concern when dealing with dynamic re-planning of VIs is how to deal with existing service requests (i.e. already planned, and deployed virtual infrastructures) during the reconfiguration time of the given VI. From the pure business perspective, service disruption considerations are of capital importance, since there is no re-planning that can affect any of the currently provisioned service requests. This approach may not provide a globally optimal solution for the planning problem. However, it will ensure the infrastructure provider will meet the expected quality of service required in terms of disruptions. On the other hand, Dynamic Virtual Network Embedding approaches aim at reconfiguring the mapped virtual networks in order to recognize the resource allocation and optimize the global utilization of the substrate resources.

Dynamic re-planning might ensure that all service requests can be supported in an efficient manner through scaling up or down

This issue is analyzed in [FAPZ11]. They realize that most of the service requests rejections are caused by the bottlenecked substrate links. In order to improve the rejection ratio and the load balance in the substrate network, they propose a reactive and iterative algorithm (called virtual network reconfiguration). The algorithm just runs when a VI request is rejected. It works as follows. In first place it sorts the mapped virtual nodes by their suitability for migration, then it migrates the most suitable virtual node and its attached virtual links to another substrate node, and tries to map again the request. If the network cannot be mapped, the next iteration of the algorithm migrates the following virtual node and the process is repeated until the whole request is mapped or until a predefined number of iterations. Performance results presented a significant increase of mapped requests after the reconfiguration algorithm is applied. Dynamic re-planning is also considered in [BFJ+10] by means of migrations when service access position changes, and in [ZA06], where a heuristic uncoordinated is proposed to reduce the cost of periodic access position changes. Following the business considerations within the GEYSERS project, and the ecosystem of our proposal (service delivery framework), we consider that any virtual infrastructure (i.e. service) that is already provisioned cannot be disrupted by any dynamic re-planning procedure.

8.2.2 *Dynamic virtual infrastructure re-planning*

Information regarding the volume and type of service requests is not precisely available in advance of the requests to the VI providers. Cloud services can scale up and down on demand. Therefore, dynamic adaptation of the infrastructure to the elasticity of the Cloud services requires constant changes. The mechanisms to update a given virtual infrastructure can be either automatically or either manually triggered by various factors and events, having as main objectives: (i) to support the upcoming connectivity services requests that cannot be served by existing VIs; and (ii) to optimize the utilization of network and IT resources. The automatically triggered are those described previously emerging from the cooperation of both the SML and the NCP with the LICL components.

However, for every planning period t the volume of the service requests can be described by a probability distribution function (pdf) that can be estimated based on history observations. In practise, this could be achieved by taking a weighted average on the traffic demand over the most recent periods e.g. using the Non-linear Autoregressive Analysis (NAR). For a detailed description on the subject the reader is referred to [TAG13].

Once this information becomes available, an optimization criterion is selected and the optimal virtual infrastructures that can support the estimated services are identified in terms of both topology and resources. In this work, we considered that the optimal VIs that can support the estimated services are identified in terms of both topology and resources. We considered that the optimal VIs are obtained minimizing the energy consumption of the underlying substrate, through the following expected cost:

$$\min \quad E_{\xi_\tau}[\textstyle\sum_t N_t(\gamma, \xi) + \sum_t \delta_t(\mu, \xi)] \tag{38}$$

whereby N_t is the power consumption of the optical network resources γ at time t, δ_t the power consumption cost of computing resources μ at time t and ξ is a random vector that contains the uncertain parameters (i.e. traffic demands) that are involved in the planning process. Details regarding the power consumption models for the optical network and computing resources can be found in [TAG+11b, GTAP12].

However, for the sake of completeness these models are summarized as follows. The present approach is focusing on optical network technologies based on WDM utilizing OXCs nodes to perform switching and facilitate routing at the optical layer. The overall network power consumption model is based on the power-dissipating (active) elements of the network that can be classified as switching nodes (OXC nodes), and transmission line related elements. More specifically the OXCs assumed are based on the Central Switch architecture using MEMSs, while for the fibre links a model comprising a sequence of alternating single mode fibre and dispersion compensating fibre spans together with optical amplifiers to compensate for the losses is employed. The details of these models are described in [TKP+11] with the only difference being that the current work assumes wavelength conversion capability available at the OXC nodes. For the computational resources, a linear power consumption model that mainly concentrates on the power consumption associated with the CPU load of IT resources is assumed and is described via the following linear equation [VLM+09]:

$$E_{st}(\upsilon_{st}) = \rho_s^i + \rho_s^b \upsilon_{st} \tag{39}$$

whereby E_{st} that is the total power used for utilizing a portion υ_{st} of the maximum processing capabilities of IT server s at time t and ρ_s^i, ρ_s^b are parameters describing the power consumption of the IT server s at idle state and per utilization unit, respectively [TAG+11b]. In addition to the power consumption due to data processing, a 100% power overhead due to cooling has been incorporated in the power consumption model above described. Consumption models are the same as the ones utilized in previous Chapter 6.

At the same time, a set of constraints should be taken into account including: (i) that the planned infrastructures have sufficient optical link capacity for all demands to be transferred to the IT servers, (ii) adequate IT server resources such as CPU, memory, disk storage to support all requested services.(iii) specific capabilities of the underlying physical infrastructure such as wavelength conversion, and (iv) protection from possible network or IT infrastructure failures, or specific security requirement through physical isolation. The complete formulation for these constraints is part of the work presented in [ATS13].

In order to solve the above stochastic problem numerically, it is assumed that the random vector ξ has a finite number of possible realizations. Each one of these realizations is called scenario, and each scenario holds a known probability distribution function. Thus, in order to extract this information, the NAR method is adopted to predict the traffic demands for the upcoming time periods due to its inherently low computational complexity and high accuracy.

However, due to the large number of scenarios involved in the optimization, exact evaluation of equation 38 is not possible. To address this issue, the Sample Average Approximation technique has been integrated with Lagrangian Relaxation and Dual Decomposition to achieve fast convergence to the optimal solution.

The performance of the proposed stochastic re-planning scheme is examined using the COST 239 reference topology [O'M96] in which randomly selected nodes generate traffic demands that need to be served by a set of IT servers. The granularity of service duration for the generated services is one hour. Furthermore, we assume a single fibre per link, 40 wavelengths per fibre, wavelength channels of 10Gb/s each and that each IT server can process up to 2Tb/s and its power consumption ranges from 6.6 to 13.2KW, under idle and full load, respectively. The following scenario has been studied: i) 4 source nodes generate demands normally distributed, ii) the number of arrivals in any given time interval $[0, t]$ follows the Poisson distribution with mean value 2 hours, iii) service times follows the exponential distribution with mean value 2 hours, iv) a single type of services has been considered that require instant access to the IT servers, v) each wavelength requires 10Tb/s of processing power.

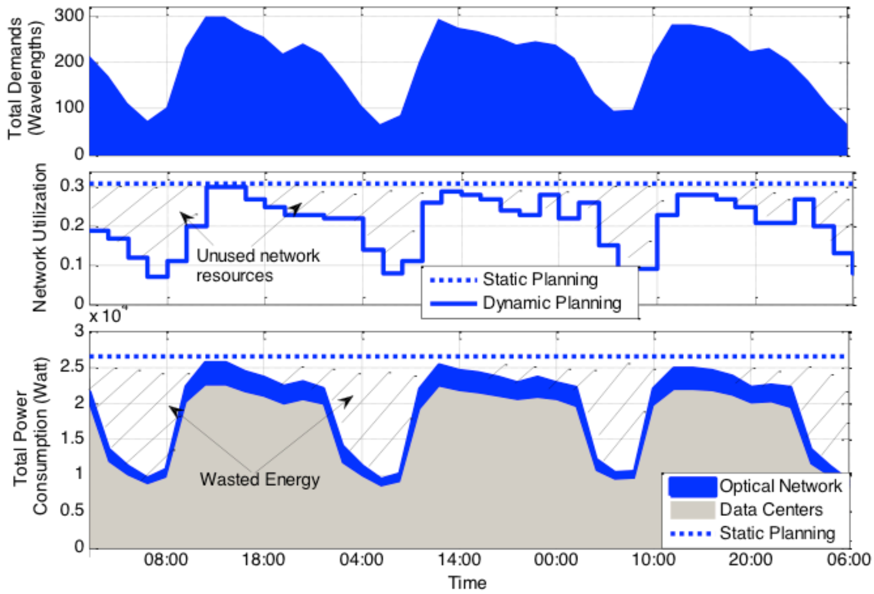

Figure 43: Traffic demands in terms of wavelengths and comparison of various planning schemes over time

Based on history observations for traffic demands recorded in the Pan-European network GEANT for a specific time period, the model is applied to estimate the traffic distribution for future time periods. Once this information is obtained, a set of traffic scenarios is generated using Monte Carlo simulations and the sample average approximated problem is solved to identify the optimal VIs for this predicted traffic distribution. The traffic distribution and the evolution of these traffic demands over time are depicted in the upper graph in Figure 43.

It is worth to mention that two approaches are considered for comparison with regards of the energy consumption of the . On the one hand, the static planning, which refers to the ideal case where (i) all the demands are known in advance, and (ii) virtual infrastructures are planned in advance for the highest volume of requests that must be supported over time. On the other hand, the proposed dynamic re-planning, which provides periodic updates over the virtual infrastructures.

In terms of resource allocation, the dynamic re-planning approach follows the optimal mapping policy defined in [ATS13], where an energy-aware planning algorithm is proposed. Authors in [ATS13] propose a subsequent algorithm combining sample average approximation, Lagrangian relaxation and dual decomposition to achieve fast convergence to the optimal solution. The consumption models of both the optical nodes and data centres are defined at the beginning of this section. In terms of resource utilization, it can be observed that by means of applying dynamic re-planning techniques, the amount of optical network resources allocated to the VIs is significantly lower (about 30%) than these required in the worst case of static planning.

The upper graph in Figure 43 illustrates the evolution of the traffic demands over time. The lower graphs of Figure 43 show the optical network resources allocated to the planned VIs and the total power consumption when applying traditional static planning and the proposed dynamic re-planning. Static planning refers to the case where virtual infrastructures are planned in advance for the highest volume of requests that has to be supported over time. Note that by utilization of optical network resources we identify it as the ratio of the number of wavelength links that are used over the total number of available wavelength links.

Finally, in terms of power consumption, it can be observed how with the static planning significant amounts of energy are wasted due to the unused resources. In the other case, the energy consumption is optimized as expected due to the energy-aware allocation strategy adopted [ATS13]. The optical network is responsible for 8% - 17% of the total power consumption in the system, which could not be ignored. There might be the case where different allocation strategies are adopted for the dynamic planning case, but it has been left out of this proposal. For further details on the comparison of different algorithms the reader is referred to [ATS13].

In fact, the benefit of dynamic and periodic re-planning of the VIs over the PI. However, that benefit achieved through dynamic VI re-planning is very much dependent on the VI re-planning time granularity, the sensitivity of the triggering mechanism and the optimization objective chosen.

For example, there might be some cases where it is better to re-plan the VIs each five minutes (short periods of time), due to the service characteristics, e.g. mobile cloud computing; while there might be some other cases where re-planning will be optimal for long periods of time. Besides, considering virtual infrastructures are provisioned as services, business service disruption should be also considered in the interval of re-plannings, i.e. although re-planning all the virtual infrastructures every five seconds would result in an optimal solution in both resource utilization and energy consumption, it would be completely inoperable in reality due to constant service disruption.

In order to analyze the impact of the inter-planning duration time (time between two different and consecutive re-planning procedures are triggered), and with the simulations set up considered above, the comparison of the static planning, and the optimal dynamic planning together with different inter-planning times duration for the proposed scheme have been included.

Figure 44 depicts the average network utilization for both the extreme cases, i.e. optimal dynamic and static planning, and the effect of varying the inter-planning time duration. It can be clearly seen how the higher the granularity is in terms of inter-planning time duration the lower is the network utilization. In essence, the more rapid the re-planning mechanisms are triggered, the more optimal is the network utilization.

On the other hand, in terms of energy consumption, Figure 45 provides a very similar results. The higher the granularity in the inter-planning time duration, the lower the total power consumption is. However, with the energy consumption it can be observed that it is even more difficult to obtain an optimal value, since it requires high granularity in the normalized inter-arrival time, which might not be feasible in actual deployments.

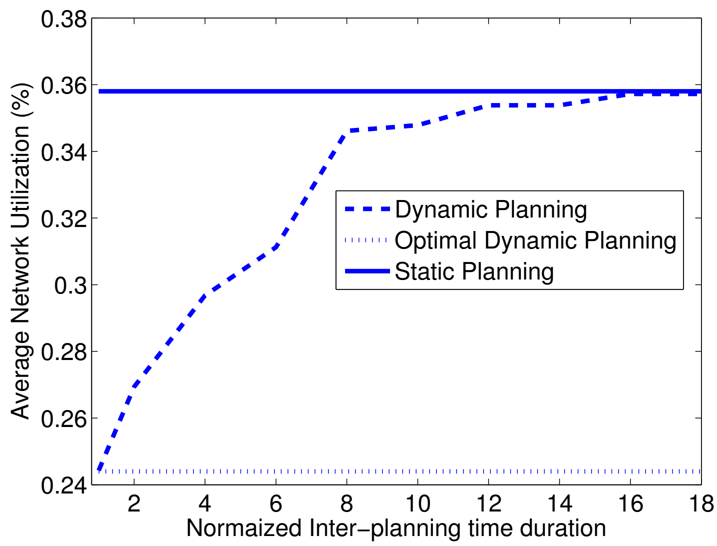

Figure 44: Impact of inter-planning time duration on the utilization of optical network resources

8.3 A REAL USE CASE: DISTRIBUTED ENTERPRISE INFORMATION SYSTEM

This section presents a practical example on how the proposed virtual infrastructure provisioning can be used to converge IT regions (i.e. DCs) and optical network resources, and how the Enhanced(+)

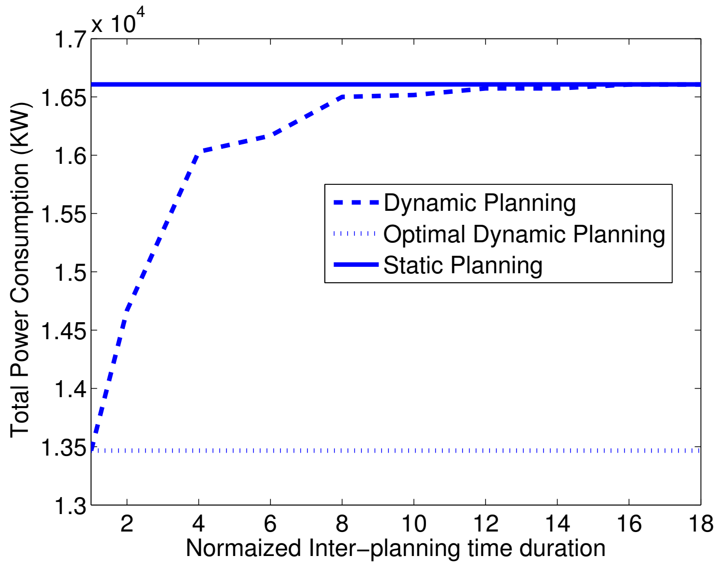

Figure 45: Impact of inter-planning time duration on the total power consumption

Network Control Plane (NCP+) can be used by a real system deployed jointly with the SML to coordinate cloud and network resources composing a virtual infrastructure. The selected distributed application is representative for the enterprise-cloud class of appliances from the network and computing resource consumption. As the CPU utilization of the different VMs composing the distributed application varies from VM to VM, this creates the basis for optimizing the allocation of VMs to physical resources by taking into consideration the energy impact of oversubscribing the physical hosts. This is possible because some VMs consistently have a lower CPU utilization independent of the concurrent load. Thus, the presented application can be used for showing how energy-aware allocation policies can be used for optimizing both the virtual (software) and physical (servers and optical network connections) resources.

A distributed-EIS is composed of multiple load-balanced query-intensive application-servers and database systems, concurrently serving multiple users

A Distributed Enterprise Information System (EIS) is composed of multiple load-balanced query-intensive application-servers and database systems, concurrently serving multiple users. In a dynamic EIS, the number of users and frequency of queries changes, such that the network and computational demand vary as well. In order to validate the response of the distributed system to the changing user loads, we specify what the users' performance expectations are. For this we use consumer-agreed SLAs [ARB12] containing the performance invariants in terms of response times and load distribution. The SLAs are also used for scaling the computational and network resources of the virtual infrastructure through the re-planning functionality described in Section 8.2.2. The data used for generating the user load is obtained from empirical analysis of an existing EIS system [AOD+13, ARB13] and from existing benchmarks [Inc13] for Enterprise information systems including analytic and business information warehouses. The performed experiments show scaling under different types of load conditions.

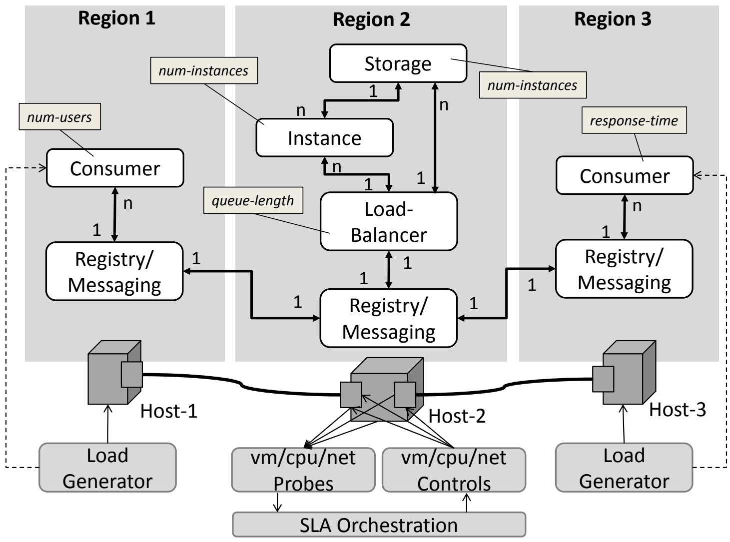

Figure 46: Distributed Enterprise Information System overview

The EIS is composed of four different logical entities: Load Balancer (LB), Worker Instance (WI), Storage (DB) and Enterprise Information System Consumer (EIS-C). The LB provides the logic by which Consumer requests are allocated to processing entities (WI). The algorithm used for load distribution is Power Saving, where requests are sent to a WI until the instance is full and a next one will be spawned and used. The WI executes requests either locally or on the DB, depending on the request type. The EIS-C simulates a variable number of parallel EIS users which are sending requests according to a given execution plan. All the service entities are implemented as Distributed Open Service Gateway initiative (OSGi) services and use a central registry for discovery.

The virtual infrastructure required for running the EIS is first created to allow the provisioning of the EIS services and then scaled based on the actual reported utilization levels of the resources. The scale process of the EIS is performed through the coordination of the SML and the NCP+ components.

In order to deploy the Distributed EIS, the complete GEYSERS service delivery framework is used, from actual infrastructure planning to control plane deployment, configuration and IT-advertisement. Therefore, first, a VI description containing the desired virtual resources is registered at the management component. Next, the VI planning algorithm takes place at the LICL and the VI is provisioned by configuring the various virtualization components in each administrative domain. This also creates resource reservations in each computational and network domain, bringing together in a single virtual infrastructure converged cloud and optical network resources.

After the VI has been provisioned, it is advertised at the Service Middleware Layer, which will then discover the available computational pools and the network resources. Then, the NCP+ is deployed and the IT advertisement process starts, coordinating the SML and the NCP+. The geographic locations for running the EIS services are selected at the GMPLS+ deployment phase. At this stage, the application description will be registered at the SML, containing the EIS service entities and the dependencies between them. Also, the monitoring metrics for each service are specified. These metrics will later be used for determining services' performance and the health of application SLAs.

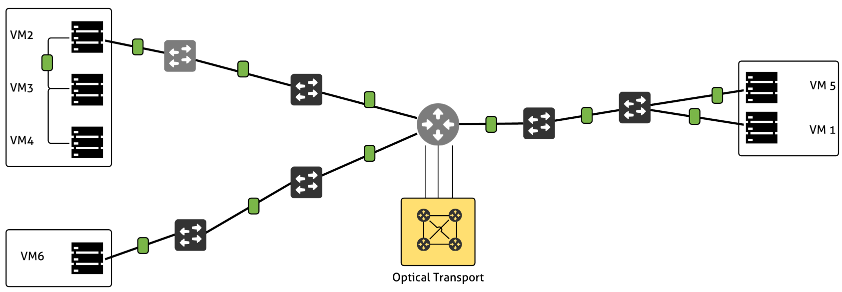

Figure 47: Distributed EIS test-bed

Figure 47 depicts how the distributed EIS application is deployed in a test-bed composed of network and computing resources belonging to different organizations. The computing sites are connected through two different networks: one deployed over optical equipment and one deployed over Ethernet devices. The former is used by the services composing the EIS for exchanging data payloads, while the latter is used for signalling between the different management components of the GEYSERS stack.

Once the GEYSERS components have been deployed and correctly configured to control and operate over the corresponding scenario, the SML will then request the creation of an optical connectivity service between each pair of IT regions. This network connectivity is realized through the NCP+ deployed also on top of the virtual infrastructure. The minimum bandwidth of each network connection is specified by the SML through the UNI service, and it will be later increased based on actual EIS consumers' activity. After the network connectivity has been established and signalled, the SML will begin the instantiation of EIS services in dedicated VMs according to the distributed application's blueprint specification. The list of service dependencies for the service is analyzed to find the correct service instantiation order, then the SML will create and start the service VMs.

Once that for each service its context has been resolved, a request for deploying a virtual machine with the service binaries will be sent to LICL. The SML will then wait for receiving the VM instantiation notification before marking the service as active and beginning its SLAs monitoring.

In Fig 48 we display some experimental application performance and network utilization measurements gathered while running the EIS on a small-scale test-bed composed of dual core servers with 4GB of RAM memory and gigabit network interfaces. Each EIS service was running in its own virtual machine with one CPU and 1GB of RAM allocated. In the experiment shown, the concurrent load was maintained at 10 requests per second during a 10 minutes time window. The average network traffic generated by one EIS cloud tenant was 100 MB/minute per VM, distributed as EIS-C: 86.2 MB/min WI: 142.1 MB/min DB: 65.6 MB/min. According to [13] the maximum number of requests per VM before reaching the performance threshold is 50, which is equivalent to a VM network traffic of 500 MB/min or 5GB/min network traffic for a EIS cloud tenant with 10VMs. Considering a datacentre with 1000 quad core servers, the generated network traffic is approximately 2000 GB/min or 2.5Gb/sec.

Measures are utilized as an example on when a scaling or re-planning procedure could be triggered

Based on the reported number of active sessions at the LB, the average response time measured at the EIS Consumers and the aggregated size of the EIS responses' payload (as shown in Figure 48), the SML will scale [AOD+13] the number of WI and DB service as well as the bandwidth of the virtual optical network circuits. Dynamic scale-up (or even scale-down if there are unused resources) of both IT and network resources of the virtual infrastructure over which the EIS is deployed is realized through the re-planning mechanisms aforementioned.

Measures in Figure 48 are only utilized as an example to clarify when a dynamic re-planning (scaling) could be triggered in a real-case scenario, by means of a typical distributed enterprise information system. Basically, several thresholds might be defined in each one of the monitored metrics (e.g. concurrent sessions at the LB, or average response time at the Consumers) in order to trigger the process. As an example, it could be defined a threshold to scale the virtual infrastructure when the average response time at the Consumers is greater than 3.000 ms. Therefore, in instant 14.49, as depicted in top right (b) part of Figure 48, since the measured time is greater than the example pre-defined threshold, a re-planning process would be triggered.

In Figure 49 the simulated energy consumption behaviour for the two servers hosting the VMs described above it is displayed. The simulation uses a linear power model based on Spec Power [G514] benchmarking information using the servers' average CPU utilization. The actual server CPU utilization is derived using the VMs' CPU utilization trace measured in the previous step. According to the simulation, the average server power consumption is 4.2KW/minute or 250KWh per server.

As an example, if the communication between region 1 and region 3 requires more network capacity, the SML communicates this to the NCP+, which is the element responsible of triggering the re-planning mechanism at the virtualization layer, the LICL. Then, the LICL starts the planning process considering resources that are not allocated to any virtual infrastructure, e.g. free wavelengths in the transport network. Thus, the virtual link connecting different regions of the D-EIS is modified, and the NCP+ can now update the network service according to the application needs. It is worth mentioning that, additional to the dynamic modification of the virtual optical links, the re-planning mechanisms also enable adding or removing unused resources, as well as the dynamic modification of the virtual IT pools that the D-EIS can use to deploy services of the application. This deployment of the system becomes a clear and sound example on how virtualization can be used to converge Cloud services with high-capacity optical network circuits.

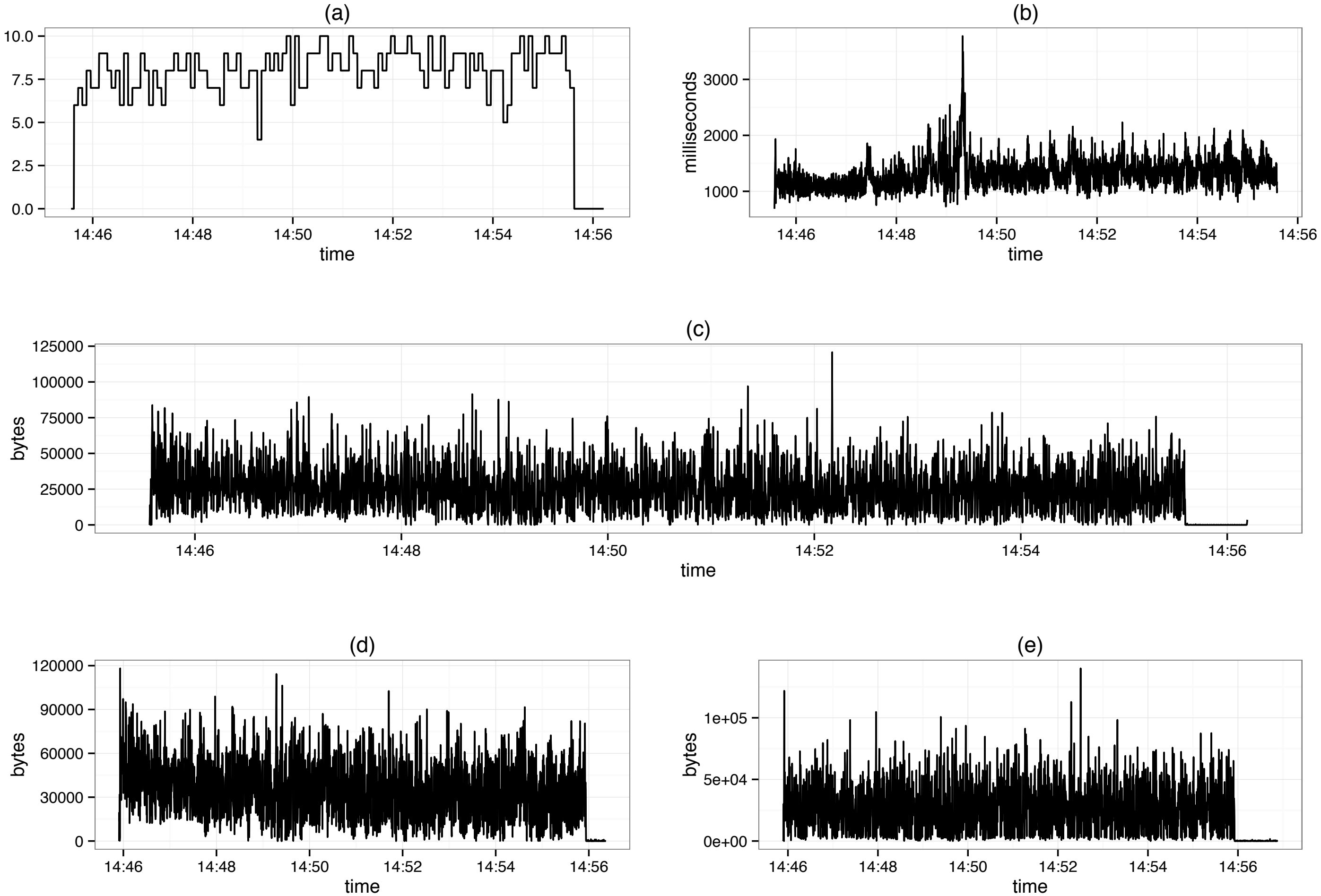

Figure 48: (a) Load Balancer number of concurrent requests, (b) Consumer request execution time, (c) Consumer network read bytes, (d) Worker network write activity, (e) Storage network write activity

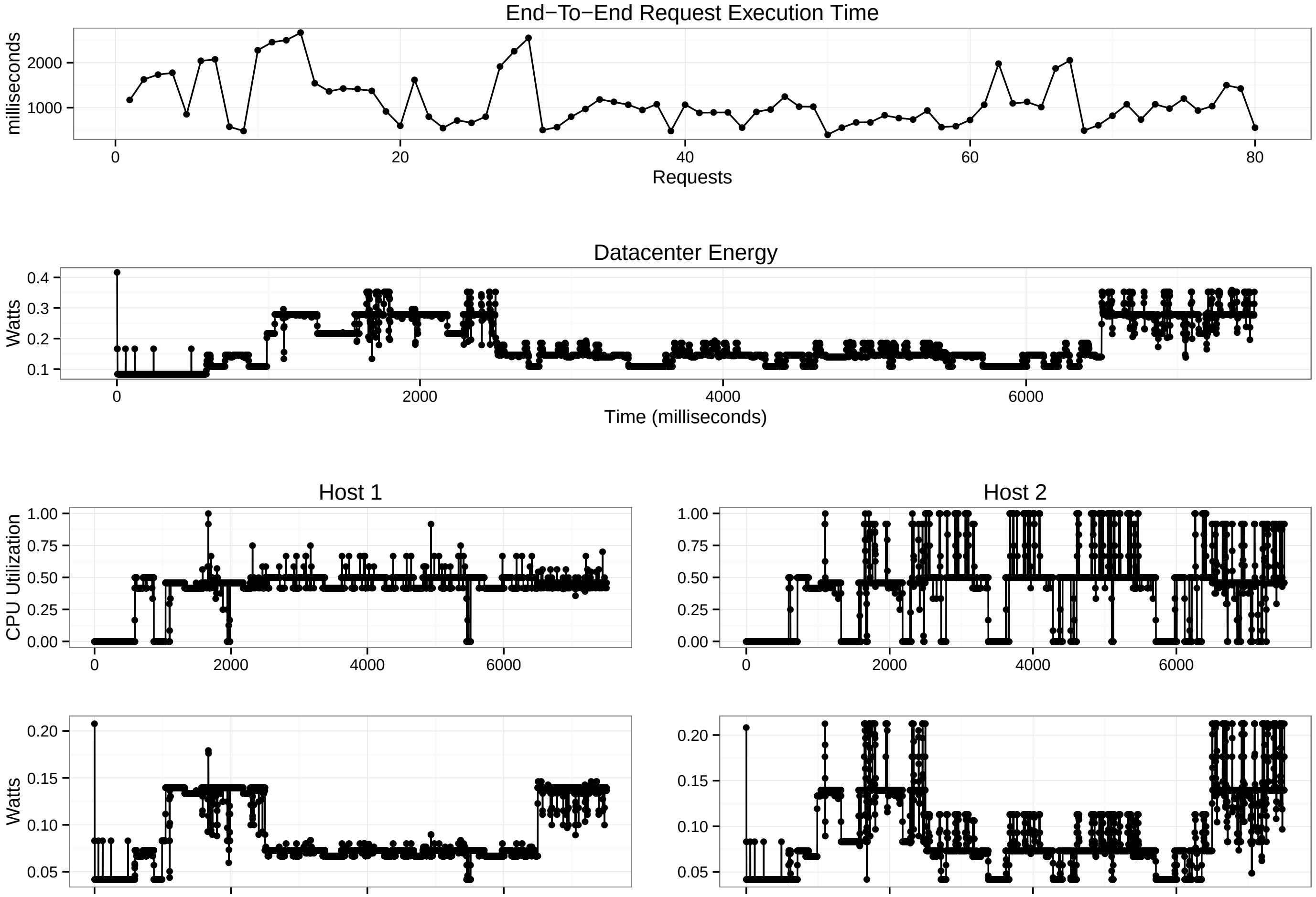

Figure 49: Simulated data centre power consumption versus CPU consumption

8.4 CONCLUSION

The virtualization approach can potentially increase the usage of the infrastructure by sharing its resources, bringing higher profits from the same underlying substrate. It clearly reduces the need of infrastructure over-provisioning since it enables infrastructure providers to dynamically adapt the infrastructure to different operators' businesses at any moment of the service lifetime. We have presented how a converged virtualization enables the creation of virtual infrastructures that address the high demanding requirements of dynamic, elastic cloud applications. The virtual infrastructure service proposed has been automated, in order to avoid manual presence in the provisioning workflow. Automation of the provisioning includes different possibilities for describing the resources that compose the virtual infrastructure and determining over which physical resources the virtual infrastructure is instantiated. Therefore, VI planning becomes a key element of the service workflow. Details of the planning algorithms are not included for the sake of simplicity, although typical optimal functions focus on the resource utilization, or even the energy consumption of the resources.

Furthermore, re-planning features of the virtual infrastructure service have been introduced to address uncertainty of the behaviour of the Cloud applications. When stochastic planning is adopted, the optical network resources allocated to the VIs are significantly lower than these required in case of static planning. It has been demonstrated how the benefit of stochastic planning can be exploited in practice by adopting dynamic and periodic re-planning of the VIs over the physical substrate. Finally, in order to show a real use case for the virtual infrastructure service and its re-planning feature, the distributed Enterprise Information System, deployed over a distributed infrastructure composed of both IT resources and optical network resources, has been presented. A virtual infrastructure is created on top of the different administrative domains, creating virtual resources to be used by the EIS. Up or downscaling of the infrastructure is performed as a function of the values monitored at the application level by the EIS.

9 ANALYSIS OF VNF SCHEDULING FOR MANAGEMENT AND ORCHESTRATION

Shōda mo tsumoreba taiboku-wo taosu.
- JAPANESE PROVERB[a]

In practice, there are many ways in which virtualization can be realized. Network virtualization has been a well-studied and well-analyzed problem both in research and industry realms. Different virtualization approaches have been proposed along several technological domains. From optical networks virtualization [NEPS11], [TAG+14], or [RTA+14], where the flexibility and transparency for the optical network infrastructures enabled by virtualization approaches, along with the capability to provide open interfaces, allows the network to be programmed in order to deliver services agnostic to the technology running in the physical layer [FSP+12], to wireless network virtualization [PS06], where several virtualization slicing technologies can be applied (e.g., frequency division multiple access, time division multiple access, frequency hopping, or even space division multiple access).

Over time, any application and service, mobile or not, will be given the potential to connect to anything at any time, from people and communities to physical things, processes, or content among others in entirely flexible and reliable ways

Over time, any application and service, mobile or not, will be given the potential to connect to anything at any time, from people and communities to physical things, processes, or content among others in entirely flexible and reliable ways. With the advent of new networking technologies, the term virtualization has been pushed one step forward. The Network Functions Virtualization approach aims at virtualizing network functions such as gateways, proxies, firewalls, and transcoders, traditionally carried out by specialized hardware devices, and migrating those functions to software-based appliances, deployed on top of commodity IT infrastructure. Network services will be composed of those virtualized network functions, which could be automatically deployed, managed, and operated. A major challenge emerges therefore in the management and orchestration layer, responsible for the chaining, placement, and scheduling of those virtualized network functions composing network services.

a Translation: with many little strokes a large tree is felled. A difficult task, e.g. removing a person or group from a strong position, changing established ideas cannot be done quickly. It can be achieved gradually, by small steps, a little at a time [Pac97]

As described in Chapter 2, in the NFV environment, ETSI NFV defines network services as entities composed of virtual network functions, which are the actual components performing the specific operations [NFV14]. Typically, network traffic associated to a given NS goes through several network functions. As authors state in [MKK14] that means a set of network functions is specified and the flows traverse these functions in a specific order so that the required functions are applied. This implies precedence requirements between functions in the same service, which is known as the formalization of the function chaining. In this regard, performance of network services will be affected by both the different composing functions' behavior and the order in which functions are processed. In essence, NFV adds new capabilities to communication networks, but it requires a set of management and orchestration functions to be added at the current model of operations, administration, maintenance, and provisioning in order to meet the expected challenges and fulfill the carrier-grade requirements [NFV12b]. The virtualization insulates the network functions from the infrastructure resources, where they run both networking and computing through a common virtualization layer. This decoupling opens the door to the exposure of a new set of entities, adding new relationships between them and the NFVI where they are allocated and scheduled.

Even with all the anticipated benefits in the telecom community for NFV, and despite the immense speed at which it has been widely accepted by both academia and industry, it is still in its early stages (i.e. the term was coined in November 2012). There still remain fundamental aspects that should be investigated and standard practices which should be established [MSG+15]. The deployment of NFV will greatly challenge current management systems and will require significant changes to the way networks are deployed, operated, and managed. Such changes are to be required not only to provide both network and service solutions, but also to exploit both the dynamism and flexibility made possible by the NFV-enabled solutions [KvdMF14, BDSZG14].

Following previous Figure 15 in Chapter 2, the right part of the image depicts the management and orchestration component of the ETSI NFV architecture, which comprises one of the fundamental research challenge within the NFV realm. Several management and orchestration platforms have been proposed in the literature in order to address those specific end-to-end management issues. [MM14, SYK+14, SYMI15, DFCV14, BLBM14]

Figure 15 in Chapter 2 depicts the overall architecture for the ETSI NFV framework. On the right part of the image it is depicted the management and orchestration component, considered as the fundamental cornerstone for the NFV technology. The management and orchestration layer within the NFV stack is responsible for the deployment and operation of the different network services.

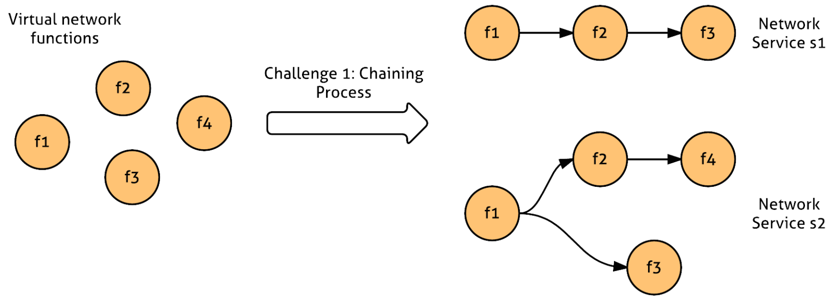

Figure 50: Challenge One: Chaining virtual network functions

The first challenge to the deployment of those services composed of virtual network functions becomes the composition process of the NS itself

To achieve the expected economies of scale from NFV, physical resources (and virtual) must be used efficiently. It has been that default deployment of some current use cases (e.g. virtual routing function [BFREGE13]) may result in sub-optimal resource allocation and consumption [VMB15]. Management and orchestration component must deal with all the associated challenges on allocation of NFV-based services and deployment and execution of their components (i.e. VNFs).

The first challenge to the deployment of those services composed of virtual network functions becomes the composition process of the NS itself [MKK14], i.e., how the virtual network functions are chained together to compose a NS, while still considering the possible dependencies, precedence, and connections between them. Authors in [MKK14] propose a model for formalizing the chaining of NFs. To this end, for each service deployment request, their approach constructs a forwarding graph which is deployed onto the physical infrastructure considering the functions have special requirements.

Service providers will need to face such a challenge to deploy customized and dynamic NFV-enabled network services. It nearly becomes obvious that the second challenge can be identified as the embedding process, i.e., where in the NFV infrastructure the virtual network functions will be allocated. Different servers in the NFVI will have different processing capabilities, or different hardware characteristics, which will affect the service performance. Efficient algorithms to determine on to which physical resources are the network functions placed are required. It must also be considered the capability to move functions from one server to another for such objectives as load balancing, energy efficiency, or resiliency.

In fact, this task of placing functions is directly related to the virtual infrastructure embedding or allocation problem [FBTB+13]; while the migration of functions during execution time may be seen as the equivalent of the dynamic re-planning of virtual infrastructure [RTA+14], and therefore it may be formulated as an optimiza-

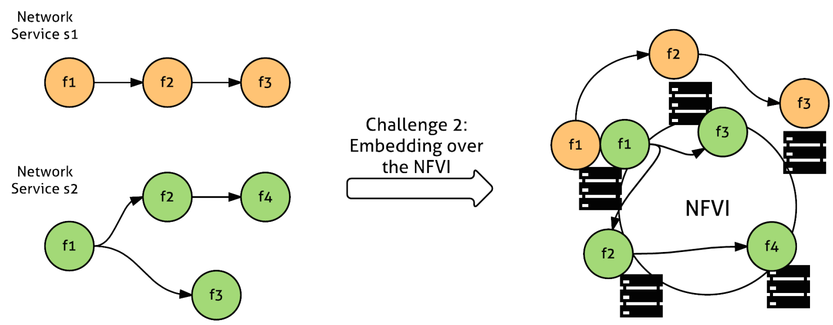

Figure 51: Challenge Two: Embedding or allocation virtual network functions

tion problem. The approach has been followed by different works in [BKH+14, MDT14, BTK14, BB15].

the second challenge can be identified as the embedding process, i.e., where in the NFV infrastructure the virtual network functions will be allocated

While this placement is a challenge for all the virtual network functions processing traffic continuously, e.g., DPI, there are other specific functions which are only executed during a certain time period, e.g., virtual PCE, which is a fundamental building block for traffic engineering systems as MPLS and MPLS [FVA06], or multi-domain virtual forwarding function, as presented in [BFREGE13], which computes the path between two independent administrative OpenFlow-enabled networking domains. A new challenge comes into the arena for the last group of virtual network functions, the scheduling, i.e., when is it better to execute each function in order to minimize the total execution time without degrading the service performance and respecting all the precedences and dependencies between the functions composing the service at the same time.

Given the fact that those functions must utilize the same resources in a VM's operating system, it is possible to use scheduling techniques to allow the functions to share the resources in an optimal manner. We defined thus the complex scheduling approach for virtual network function orchestration and management.

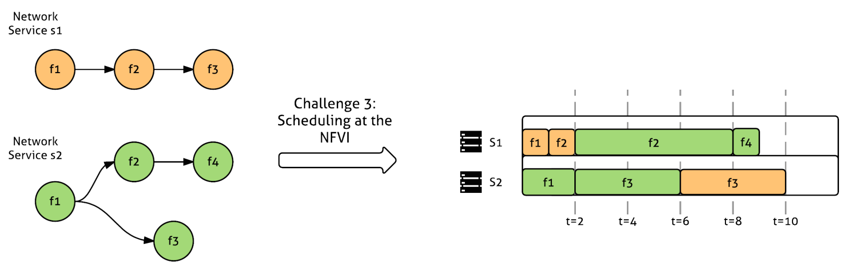

Figure 52: Challenge Three: Scheduling virtual network functions

9.1 COMPLEX SCHEDULING PROBLEM MODELING AND FORMULATION

This section contains the description of the model associated to the VNF scheduling problem which has to be solved. In the model a number of sets are used. F represents virtual network functions, N represent network services, which are composed of different chains of virtual network functions, and S represents servers, which are the elements responsible for processing different functions and services. Each network function $f \in F$ belongs to one of the network services $n \in N$. In fact, each network service is constituted of a number of network functions. The relation is modeled by sets $F(n)$, which, for each network service, contains all network functions that constitute it. The notion of network services is also indirectly modeled by sets $F(f)$ that define relations between network functions, i.e., for each network function we define a set (possibly empty) of network functions that cannot be initiated before the considered network function is successfully executed. The sets are listed below:

F network functions

N network services

$F(n)$ network functions belonging to network service n

$F(f)$ network functions that cannot be executed before finishing the execution of network function f

S servers

There is also a set of constants in the model, which are relevant for the different calculations.

$t(f,s)$ time needed by server s to execute network function f

A weight of the finish time of the last served network function

M infinity; a sufficiently large constant in practice

Constant $t(f,s)$ is responsible for a server classification. By setting different execution times for different network functions on different servers, it is possible to easily create classes of servers. In addition, setting appropriate constants $t(f,s)$ to sufficiently large numbers, we can easily block some functions from being executed on particular servers. However, such an operation can be done more easily by forcing appropriate variables to be equal zero. Another constant is A. It serves as a weight to indicate which part of the objective function is more important: the finish time of the last served network service, or the sum of the finish times of all network services. The last constant is the so called “big-M" constant frequently used in MILP programs to express relations between binary and real variables.

Finally, the variables considered for the model are described below, just before the complete problem formulation:

z finish time of the last served network service

z_n finish time of network service n

v_f starting time of executing network function f

e_{fs} binary variable; 1 if network function f is executed at server s; 0 otherwise

$a_{ff'}$ binary variable; 1 if network function f is executed after f'; 0 otherwise

The objective function is defined as follows:

$$\min Az + \sum_{n \in N} z_n \tag{40a}$$

In formulation (40), the objective function consisting of two components is minimized. The first component is the time needed to execute all network services, while the second component is the sum of the times needed to execute each network service. The following constraints are taken into account in the problem.

$$z \geqslant z_n \quad \forall n \in N \tag{41a}$$

$$v_f + \sum_{s \in S} t(f,s) e_{fs} \leqslant z_n \quad \forall n \in N, \ \forall f \in F(n) \tag{41b}$$

$$v_f + \sum_{s \in S} t(f,s) e_{fs} \leqslant v_{f'}, \quad \forall f \in F, \ \forall f' \in F(f) \tag{41c}$$

$$v_f + t(f,s) \leqslant v_{f'} + M(a_{ff'} + 2 - e_{fs} - e_{f's}), \quad \forall f, f' \in F, \ \forall s \in S \tag{41d}$$

$$a_{ff'} + a_{f'f} = 1, \quad \forall f, f' \in F : \ f \neq f' \tag{41e}$$

$$\sum_{s \in (S)} e_{fs} = 1, \quad \forall f \in F \tag{41f}$$

Variable z represents a moment in time when all network services are already executed; thus, it cannot be smaller than the finish time of any network service, which is expressed by (41a). On the other hand, the finish times of single network services cannot be smaller than finish times of network functions that constitute them. The relation is modeled by (41b). Notice that in (41b) a term $\sum_{s \in (S)} t(f,s)e_{fs}$ is just a time needed to execute function f on a selected server represented by e_{fs}. We consider network services that impose various constraints on network functions they are built of. This fact is represented by (41c), in which time of executing network function f' that follows another network function f, i.e., $f' \in (P(f))$, has to be greater than the finish time of executing network function f. The next constraint, namely (41d), prevents network services from being executed in parallel on the same server—it is assumed that each server can process only a single network function at a time. In other words, consider two network functions f and f'. Assume that f is executed before f' (thus, $a_{ff'} = 0$) and both are executed at server s. If all the conditions are met, constraint (41d) reduces to $v_f + t(f,s) \leqslant v_{f'}$, which means that the starting time of executing network function f' has to be after the finish time of executing network function f. On the other hand, when at least one of the mentioned conditions is not satisfied ($a_{ff'} = 1$ or $e_{fs} = 0$ or $e_{f's} = 0$), constraint (41d) reduces to $a \leqslant b + cM$, where $cM \gg a, b \geqslant 0$; thus, it is always satisfied regardless the values of the variables. Obviously, constant M has to be sufficiently large—in the considered problem it can be equal for instance to $\min_{s \in (S)} \sum_{f \in (F)} t(f,s)$, which is a minimum time needed to execute all network functions on the fastest server. Finally, constraint (41e) ensure that not all variables $a_{ff'}$ can be equal to 1, while constraint (41f) ensure that all network functions will be executed.

9.2 SIMULATION AND RESULTS ANALYSIS

This section describes the heuristic algorithm utilized for the problem resolution, as well as it contains an example execution for a single run of one simulation. We also discuss and analyze the obtained results.

9.2.1 *Heuristic algorithm*

The heuristic method used in our research is a variation of a greedy approach that in each iteration schedules a network function which minimizes the overall time assuming that the remaining network functions are scheduled on the fastest finishing servers. Assume that network functions in set F are ordered in a way that if $f \in F$ is before $f' \in F$ in the order, then f can be executed before f'. Obviously there is a large number of such feasible orders. We do not take any additional assumptions concerning this matter. Therefore, the assumed order can be any of the orders satisfying the previously described constraint. The method is formally stated in Algorithms 1, 2, 3, and 4. Algorithm 1 being the main body of the procedure. In each iteration of *while* loop, it tests all remaining network functions, and selects the one that will minimize *time* needed to realize all the services.

Algorithm 1 Heuristic algorithm

```
A ← F
while A ≠ ∅ do
    toSchedule ← NULL
    time ← ∞
    for all f ∈ A : ∀f′ ∈ A, f ∉ F(f′) do
        RunOnBestServer(f)
        for all f′ ∈ A : f′ ≠ f do
            RunOnBestServer(f)
        currentTime ← TotalTime
        delete all temporary schedules
        if currentTime < time then
            time ← currentTime
            toSchedule ← f
    ScheduleOnBestServer(toSchedule)
    A ← A \ {toSchedule}
return
```

The algorithm relies on greedy scheduling presented in Algorithm 2. The greedy scheduling assigns a network function to a server that will finish it as early as possible. Notice that in the algorithm using available slack time is not allowed; thus, each greedily assigned network function cannot be followed by any other network function already assigned to a considered server.

The total execution time is computed by Algorithm 3. It is a straightforward iteration through all network functions that returns their latest finish time. It is worth to notice that after calling Algorithm 3 all temporary schedules made by Algorithm 2 are deleted. The only permanent schedules (not deleted in the future) are made by Algorithm 4, which is basically calling Algorithm 2 that makes all schedules permanent. As assignments can be either temporary or permanent it is worth to explain the meaning of variables e_{fs} and v_f in this context. In all the presented algorithms, the variables represent the current state of the scheduling taking into account both permanent and temporary assignments.

Algorithm 2 RunOnBestServer function

function RUNONBESTSERVER(f)
  $startTime \leftarrow 0$
  for all $f' \in F, s \in S : f \in F(f'), e_{f's} = 1$ **do**
    if $startTime < \nu'_f + t(f', s)$ **then**
      $startTime \leftarrow \nu'_f + t(f', s)$
  $endTime \leftarrow \infty$
  $bestServer \leftarrow NULL$
  for all $s \in S$ **do**
    $serverStart \leftarrow startTime$
    for all $f' \in F : e_{f's} = 1$ **do**
      if $serverStart < \nu'_f + t(f', s)$ **then**
        $serverStart \leftarrow \nu'_f + t(f', s)$
    $serverEnd \leftarrow serverStart + t(f, s)$
    if $serverEnd < endTime$ **then**
      $endTime \leftarrow serverEnd$
      $bestServer \leftarrow s$
  temporarily schedule f on $bestServer$
  return $endTime$

Algorithm 3 TotalTime function

function TOTALTIME
  $finishTime \leftarrow 0$
  for all $f \in F, s \in S : e_{fs} = 1$ **do**
    if $finishTime < \nu_f + t(f, s)$ **then**
      $finishTime \leftarrow \nu_f + t(f, s)$
  return $finishTime$

Algorithm 4 ScheduleOnBestServer function

function SCHEDULEONBESTSERVER(f)
  RUNONBESTSERVER(f)
  make the schedule of f permanent

9.2.2 *Results analysis*

In order to perform the evaluation of the problem, we have considered different scenarios where to evaluate the scheduling algorithm. The scenarios defined in order to evaluate the effectiveness, performance, and efficiency of the proposed scheduling are defined in terms of: (i) number of available services in the NFV infrastructure so they can process the functions composing the services; (ii) the computing capacity of each server to process all the assigned functions; and (iii) the complexity of the different network services, i.e., the number of functions composing each service.

For the topology of the network services we have used a tree-based generator, which is compliant with the ETSI network service descriptor as defined in [NFV12b]. This means the network service has a unique entry point, i.e., one unique network function being entry point, and may have one or more termination points, i.e., one or two more virtual network functions where the network service ends. Thus, the chains composing the service will have always have the form of a tree.

The following table contains the description of the scenarios considered for evaluation. There is one major motivation to consider such different scenarios, which becomes the key to analyze the two possible scenarios for the actual NFV deployment into production networks. Either the functions are deployed into the huge DCs located in the core networks, with high-computing capacities or either the new trend on edge computing gains momentum and the functions are executed by micro-servers located close to the network edges. Such trend is being defined and standardized within the ETSI in the corresponding industry standardization group [MEC14]. Mobile-Edge computing offers different stakeholders with cloud-computing capabilities and an IT service environment at the edge of the mobile network. This environment is characterized by ultra-low latency and high bandwidth as well as real-time access to radio network information that can be leveraged by applications. Together with NFV, mobile-edge computing will pave the way in the access towards fully virtualized 5G core networks, with dynamic and optimized placement and scheduling of network functions.

Figures 53, 54, 55, and 56 contain an iteration example of the heuristic implemented for the case of three network services and six available servers, and six network services and six servers respectively. The first case, Figure 53 contains the set of network services to be scheduled on the NFVI, $ns1, ns2, ns3$. The functions are represented by colored circles, while each arrow depicts the precedence of each one of the functions. Basically, arrows in both Figures 53 and 54 are utilized to describe the $F(f)$ expression of the model for each function. Therefore, in 53, the function $f3$ cannot start until $f1$ and $f2$ have

Table 3: Scenarios considered for evaluation

Scenario ID	Number of available servers	Computing capacity	Complexity of NSs
S.1	High number of available servers (30)	Low computing capacity; i.e. high processing time t for each function f executed in the set of servers S	NSs composed of less than 4 virtual network functions
S.2	High number of available servers (30)	Low computing capacity; i.e. high processing time t for each function f executed in the set of servers S	NSs composed of more more than 6 and less than 10 virtual network functions
S.3	Low number of available servers (5)	High computing capacity; i.e. low processing time t for each function f executed in the set of servers S	NSs composed of less than 4 virtual network functions
S.4	Low number of available servers (5)	High computing capacity; i.e. low processing time t for each function f executed in the set of servers S	NSs composed of more than 6 and less than 10 virtual network functions
S.5	Servers of both type available (10)	Hybrid computing capacity for each type of server	NSs composed of 1 to 10 virtual network functions

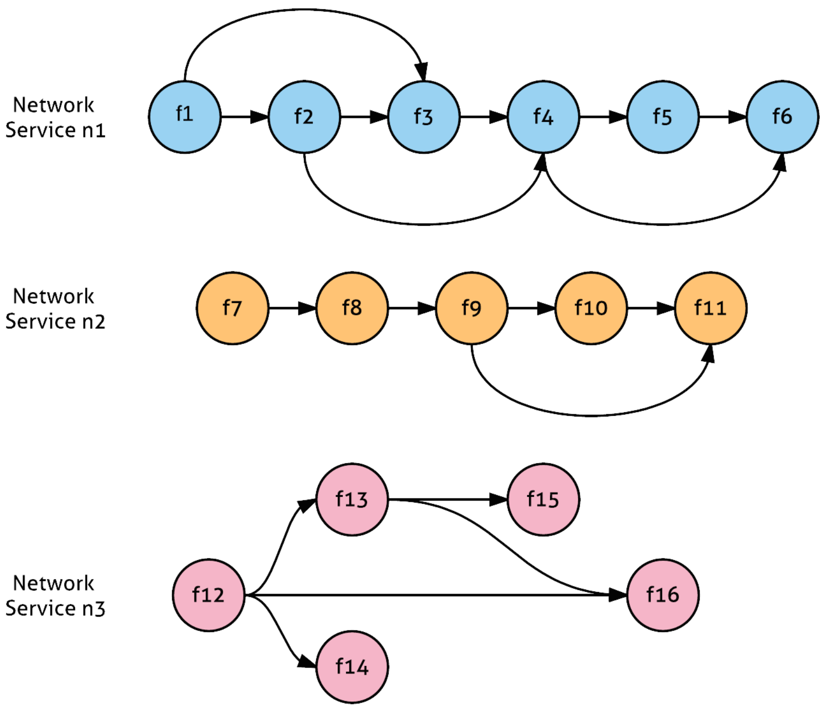

Figure 53: Set of network services

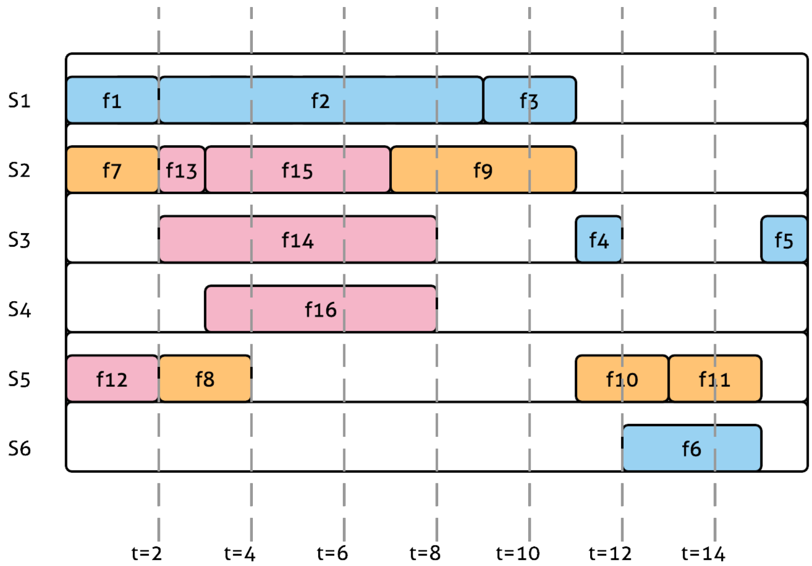

Figure 54: Schedule for the network services and six servers

ended. Figure 54 contains the schedule obtained in one execution. It can be seen how the busyness percentage of the servers in the NFV infrastructure does not go high, due to the precedence constraints of the service chains. Equally, Figures 55 and 56 contain one example on how to schedule six service chains over six different servers in the infrastructure. The percentage of busy time for all the servers in this case becomes higher, due to the possible parallelization of some functions within the same service, e.g. f11, f13, and f14 in network service ns3 can be executed in parallel in order to terminate the service. The times required by each server to compute each network function are randomly generated between one and ten, and they are described in Appendix D, within Tables 5 and 6 respectively.

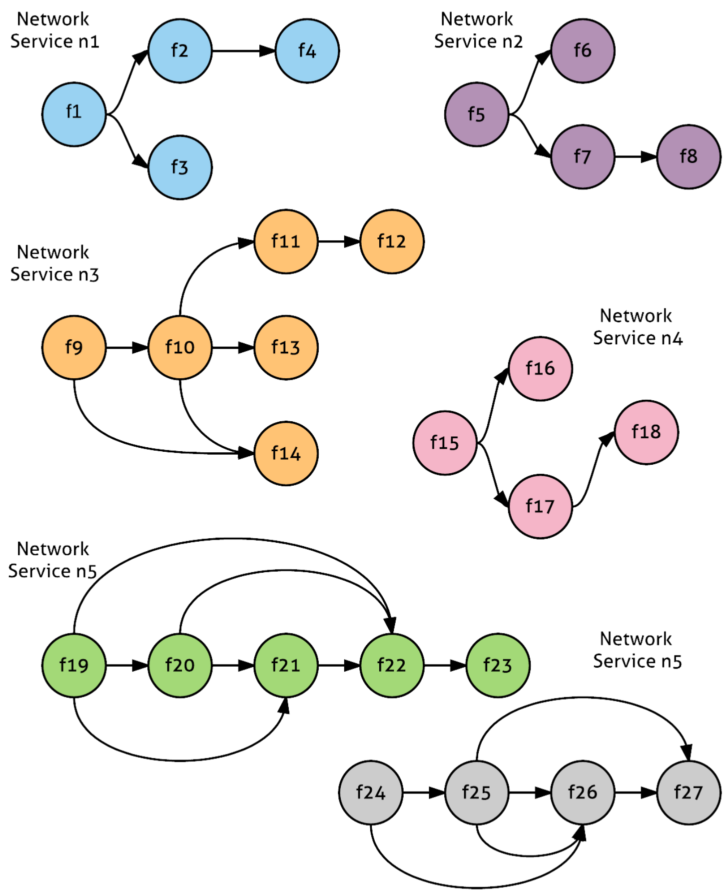

Figure 55: Set of network services

For each scenario defined in Table 3 we have randomly generated the processing time of the different services, and thus the functions, between 1 and 10 units, depending on the type of server. Like aforementioned, the chains generated are ETSI service descriptor compliant and hold the form of trees with an unique service entry point. For each scenario we have executed 200 iterations on an standard high-volume IT server.

Figure 57 contains the results for the total execution time z in each scenario. First result to highlight is the one in scenario S.4, which clearly performs as the worst case for the scheduling approach. This scenario is the one that corresponds to a low number of available physical servers responsible for performing complex network ser-

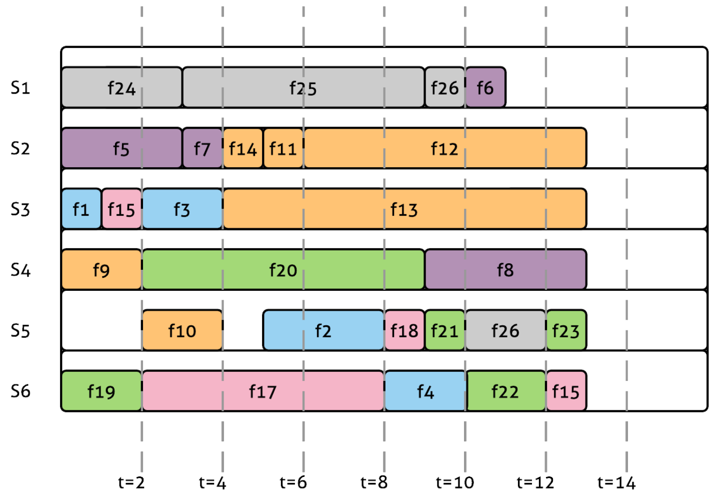

Figure 56: Schedule for the network services and six servers

vices, i.e. composed of more than six and less than ten virtual network functions. The result clearly demonstrates that although having lower processing times due to the higher computing capacity of these servers, the low number of total servers and all the precedences constraints between chains of virtual network functions generated to simulate the network services are a key element to consider when analyzing the deployment of network services composed of virtual network functions. Moreover, the results in terms of server utilization in Figures 58 and 59 confirm that while the processing capacity of the servers is important, the flexibility is provided by a higher number of servers in the network edge such as the ones considered in scenarios S.1 and S.2. Basically, it can be said that when the number of network services to be scheduled increases, the scenarios with lower number of servers, independently of their computing capacity, behave worst mainly due to the amount of network functions to be executed simultaneously.

Furthermore, it can be seen also that the direct comparison between S.1 and S.3, when considering simple network services, there is no significant difference between having a few number of servers with high computing capacity and a considerable number of servers with low computing capacity. It is worth to mention that computing time units have been generated from one to ten within a logical manner, without considering actual processing times. However, again, when the number of network services increases to more than 10, the flexibility of having more servers enables the total execution time of the workflow to remain within reasonable terms, nearly constant up two twenty services, at the same time the total utilization time increases linearly, as

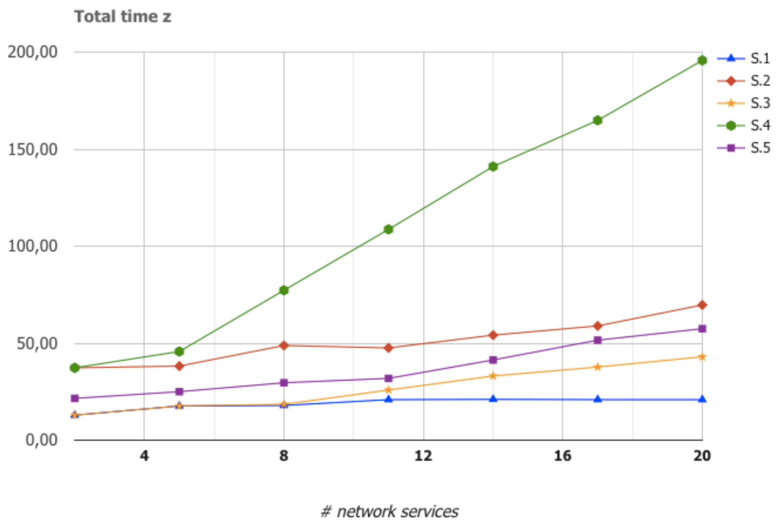

Figure 57: Total execution time z for each evaluated scenario

expected. The hybrid scenario S.5 provides reasonable results, always behaving in average between the different extreme cases.

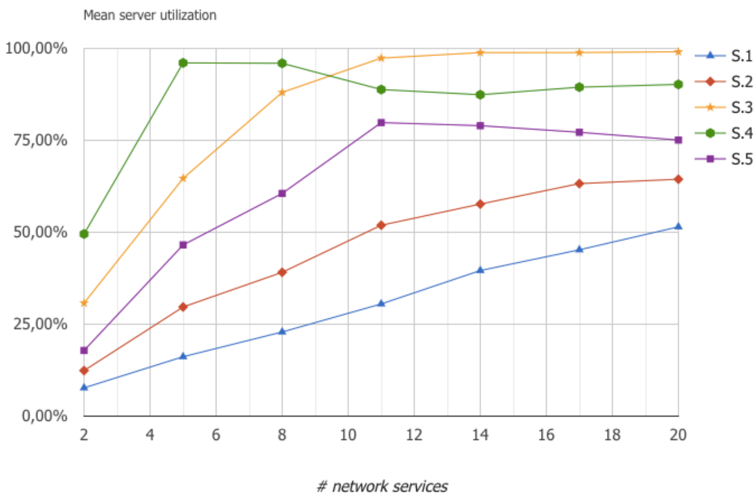

Figure 58: Mean service utilization (percentage) for each scenario evaluated

Finally, it is worth mentioning that for a small number of network services to be scheduled, i.e. less than five, independently of the complexity and the available resources (servers) in the NFV infrastructure, all the cases for mobile edge computing (S.1 and S.2) behave very similar to the cases of huge data centres (S.3 and S.4) respectively, which indicates that in environments where the number of services to be scheduled simultaneously remains small, any of the preferred scenarios for the infrastructure can be selected.

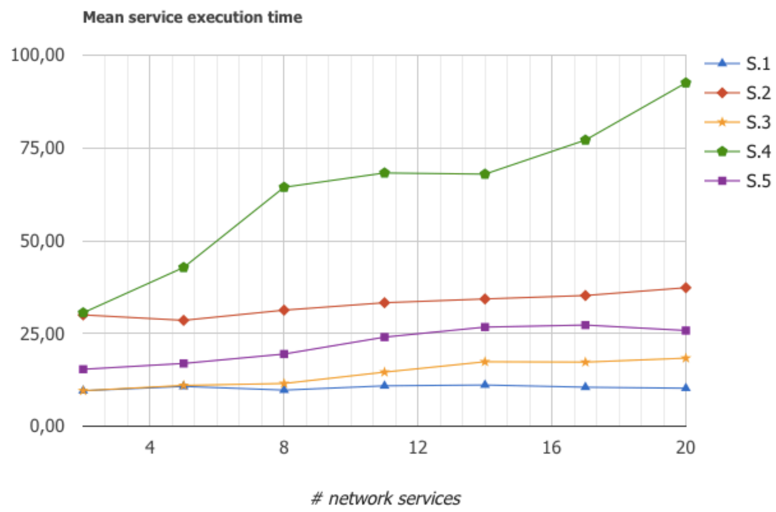

Figure 59: Mean service execution time (time units) for each scenario evaluated

9.3 CONCLUSION

Network functions virtualization is an approach, led by the European Telecommunications Standardization Institute, which aims at decoupling the network functions from the actual, proprietary hardware where they are executed nowadays by means of virtualizing them. It is seen as a very promising approach, since it basically means that telecom operators will no longer require to acquire and deploy dedicated hardware devices to provision their network services. Most of the network functions will run on standard virtualized servers by means of software, which is expected to significantly reduce capital expenditures, while at the same time the software automation reduces operational expenditures.

However, in order to achieve such objectives, ETSI defines a management and orchestration layer, responsible for the challenges introduced in the article: (i) building service chains composed of different virtualized network functions; (ii) deducing where to allocate such chains the underlying available infrastructure; and (iii) scheduling the functions in order to minimize the total execution time of the workflows or network services.

We have presented within this chapter a model to solve the third challenge associated to the virtual network function management and orchestration, since most of the related work focuses in the first two other challenges, without considering the time dimension within the telecom networks operation. We present a heuristic to solve the problem, which is a variation of a greedy approach that in each iteration schedules a network function that minimizes the overall time assuming that the remaining network functions are scheduled on the earliest finishing servers. In order to evaluate the model and the heuristic we have defined five different scenarios, which can be mapped to real-life environments considered around the NFV topic.

The evaluation of the results demonstrates that rather than considering servers with high computing capacity, the complexity of the service chains and the precedences may require a higher number of available servers in order to maximize the parallelization in the cases in which it is possible. The set of results comprehends an initial analysis of the problem, considering infinite buffers at each server, and thus waiting capacity for the functions is not considered into the problem. Future work aligned to this workflow scheduling related to the virtualization of network functions topic includes more complex scenarios as well as the inclusion into the model of both the latencies between the servers and the waiting capacities at each server.

Part IV

CONCLUSION

- "Do not try and bend the spoon. That's impossible. Instead... only try to realize the truth."
- "What truth?"
-"There is no spoon."
-"There is no spoon?"
-"Then you'll see, that it is not the spoon that bends, it is only yourself. "

10 CONCLUSION AND FUTURE WORK

Quoi que vous fassiez,
écrasez l'infâme,
et aimez qui vous aime
- François-Marie Arouet (also known as Voltaire)

Virtualization is defined as the process consisting of building a virtual resource on top of one or several physical resources, depending on the selected paradigm: aggregation or partitioning. From the networking perspective, over the recent years virtualization became a hot topic in networking research, although the term is not new, neither for networking nor for IT. In virtualization environments, the most significant challenge to be addressed is the virtual infrastructure allocation or embedding one, although not the only one. The problem appears over any networking technology, from wired to wireless domains, including converged physical infrastructures as well as coupled IT and networking infrastructures. This problem has re-gained importance in the last years due to the emergence of novel software-based abstractions, which provide fully-operational interfaces on top of those virtual resources, enabling the emergence of novel business models.

The election of the physical resources upon which the virtual infrastructure will be instantiated becomes fundamental for the virtual infrastructure operation in those virtualized environments, i.e. the election of the physical resources over which the virtual ones will be allocated. In fact, the virtual infrastructure allocation system might be seen as a policy-based system, where, based on the physical infrastructure available, and the set of requests, it will create different virtual infrastructures as a function of the policy, which will indicate the metric to optimize when creating those VIs. For example, the infrastructure provider, who is responsible for leasing those virtual infrastructures, may want to optimize the economical cost of the different instantiated virtual slices, or even the overall energy consumption of the slices.

The activities within the dissertation have been centered in the virtualization topic, pivoting around it with different important concepts within the problem.

10.1 CONCLUSION

First of all, the dissertation provides a complete overview of the virtualization realm within the last years. It provides a complete analysis and state of the art of different approaches regarding virtualization, from system virtualization to network virtualization, including paradigms, network technologies, and embedding algorithms. The state of the art compilation and analysis (refer to Chapter 2 comprehends the achievement of the first macro-objective of the doctoral thesis, as defined in Chapter 3. The state of the art comprehends:

- overall virtualization analysis, both IT and network
- generic optical networks and cloud computing analysis
- detailed network virtualization problem analysis, for both wired and wireless resources
- network virtualization environment considerations and identification of existing solutions, including novel technologies such as SDN
- analysis of the novel trends for virtualization, i.e. NFV and associated standardization efforts
- definition of the virtual infrastructure service provisioning problem and its components (e.g. requests or demands, physical infrastructure, policies)

Then, in order to address the second macro-objective, several contributions to the virtual infrastructure provisioning problem have been completed.

The first specific objective comprised the analysis of the physical substrate impact in such problem. In order to analyze the impact of the substrate, i.e. the impact of two different transport technologies, the work analyzed wavelength switching and spectrum switching in order to see which underlying technology performed better in terms of supported numbers of virtual infrastructures. This first contribution of the thesis demonstrates the importance of considering the different physical characteristics of the substrate where the virtual infrastructures will be allocated. This demonstrates to be of fundamental importance for optical networks, when considering both fixed grid and flexible grid scenarios. The sub-lambda virtualization, with greater flexibility, will become of crucial importance when converging wireless access networks with fixed networks. Results in terms of maximizing the number of virtual infrastructures clearly demonstrate that greater flexibility in the substrate allows the infrastructure provider to provision more VIs.

In detail, the blocking probability has been calculated for different randomly generated demands. In all the scenarios the flexible grid has been more effective in terms of number of virtual infrastructures requests, i.e. lower blocking probability. The analysis performed in Chapter 4 showed that the flexible grid substrate holds around 10% lower blocking probability as compared to the fixed grid scenario.

Besides, the second specific objective was related to the analysis and study of any other component of the virtualization problem, as defined in Chapter 3. Thus, it has been provided an innovative solution to the problem relaxing the isolation constraint between virtual infrastructure requests, composing clusters of requests, in order to process and provision them jointly. The solution was a two-step algorithm, which first performs clustering, and then performs the design or allocation of the clusters on top of the underlying physical substrate. The clustering included also the trade-off analysis between resource utilization and control plane scalability.

In most of the cases analyzed, the contribution required from 5% to 10% less wavelength capacity compared to any random clustering. Also, the effectiveness of the random clustering reaches a minimum between $[3,6]$ clusters, indicating the region where intelligent clustering is most in order. However, the relatively low improvement of ILP-based over random clustering indicates that more advanced clustering should be developed. For example, taking into consideration network grooming.

Finally, with regards the second macro-objective, there was still the aim to provide contributions to the community in terms of the metrics to be optimized, i.e. policy upon which the virtualization assignment must be guided. Considering the importance of energy consumption and the increasing expansion of the ICT technologies, in Chapter 6 the performance of a proposed VI design minimizing such metric has been analyzed.

In detail, the performance of the proposed energy aware VI design is compared to the demand allocation scheme where demands from each source node are assigned to its closest IT server. Comparing these two schemes, it has observed that the energy aware VI design consumes significantly lower energy for serving the same amount of demands compared to the other scheme in the order of 30%. Furthermore, it has been observed that in both schemes average power consumption increases almost linearly with the number of demands. However, the relative benefit of the energy aware design decreases slightly with the number of demands, as we get closer to the full system load.

As a major outcome of this analysis, in essence, it has been observed that in terms of energy consumption, for optical-IT converged networks it is still more efficient to set up more lightpaths to route the demands to a single server, rather than serving activating less lightpaths (shortest path) and utilizing several servers.

Additionally, mobile computation offloading has been identified as a key-enabling technology to overcome the inherent processing power and storage constraints of mobile end devices. To satisfy the low-latency requirements of content-rich mobile applications, existing mobile cloud computing solutions allow mobile devices to access the required resources by accessing a nearby resource-rich cloudlet, suffering increased capital and operational expenditures. To address this issue, in Chapter 7 an infrastructure approach based on the orchestrated planning and operation of optical DC networks and wireless access networks.

Still under the second macro-objective, and aiming at minimizing the energy consumption of the VI planning scheme, in Chapter 7 a completely converged infrastructure has been considered (wired - wireless), including delay constraints. Furthermore, the mobile devices have been included into the problem. Basically, a novel multi-objective virtual infrastructure provisioning scheme over converged wireless, optical network, and computing resources has been presented in order to a) minimize the energy consumption of the converged infrastructures; and b) to maximize the lifetime of mobile devices, by means of analyzing the optimal decision point in order to offload computational tasks.

Different observations have been made within these studies. Regarding end-to-end delay, it has been generally observed in all the scenarios that the optical network segment is responsible for less than 1.5% of the overall network delay, which makes the proposed converged approach very powerful in comparison to the Cloudlet approach. In fact, it has been observed that due to the scarcity of resources in the wireless access network, the increase in the background load in the wireless domain leads to an exponential increase in the end-to-end delay.

At the same time, the total power consumption is very much dependent on the end-to-end delay constraints. Basically, if the end-to-end delay constraints are higher, i.e. low delay required, there is the need to utilize or reserve more network resources, which in the end turns to produce higher total power consumption in the system.

In order to provision Cloud-enabled services, virtual infrastructures must hold elasticity in both spatial and temporal dimensions. While the initial contributions addressed the offline virtualization problem, i.e. all the requests are known in advance; this will not typically occur in actual environments. Cloud-enabled services are typically unknown in advance. Thus, in order to cover the last macro-objective of the dissertation, it has been also proposed a novel scheme for dynamic re-planning, coordinated with the Cloud-based applications, which basically enables virtual infrastructures as a service towards those services. This proposal considers the online problem, where requests are not known in advance, and arrive at the virtualization system online.

The proposed re-planning approach demonstrated that the benefit of stochastic planning could be exploited in practice by adopting dynamic and periodic re-planning of the VIs over the PI. It should be noted that the benefits achieved through dynamic VI re-planning are very much dependent on the VI re-planning time granularity, the sensitivity of the triggering mechanism and the optimization objective chosen.

Furthermore, a practical example on how the proposed virtual infrastructure provisioning can be used to converged IT regions (i.e. DCs) and optical network resources) has been also presented. Basically, a virtual infrastructure is created on top of the different administrative domains, creating virtual resources to be used by the EIS. Up or downscaling of the infrastructure is performed as a function of the values monitored at the application level by the EIS itself, in an automated manner.

Finally, the last stage of the dissertation has been focused on the new virtualization paradigm shift present in the community. Virtualization is moving from resources to network functions. NFV aims at decoupling the network functions from the actual hardware where they are executed. Thus, most of the network functions will run on standard virtualized servers by means of software, which is expected to significantly reduce capital expenditures, while at the same time the software automation reduces operational expenditures.

There are three well-identified challenges that need to be faced yet within the NFV community. The challenges are described in detail in chapter 9. Basically, the proposal has been focused on the definition of the third challenge, the formulation of the problem, and the initial solution based on a heuristic solution, which is a variation a greedy approach that in each iteration schedules a network function which minimizes the overall time assuming that the remaining network functions are scheduled on the fastest finishing servers.

Initial results have been obtained after evaluating five different scenarios, each one of them considering different parameters in terms of size of the service chains, processing time for functions composing the services, and type of servers (e.g. mobile edge computing scenarios, or traditional DCs). The evaluation of the results demonstrates that rather than considering servers with high computing capacity, the complexity of the service chains and the precedence may require a higher number of available servers in order to maximize the parallelization in the cases in which it is possible. The set of results comprehends an initial analysis of the problem, considering infinite buffers at each server, and thus waiting capacity for the functions is not considered into the problem.

10.2 FUTURE WORK

As for future work, it is envisaged that while research on virtualization algorithms will lose momentum, NFV and research on the three challenges will drive the virtualization community in the coming years. In fact, there is still a lot to do within the NFV community.

Information and data models for virtual network functions need to be completed, as well as their proof-of-concepts prototypes start to be implemented. Future work directly points in the NFV direction. Virtualization in the sense of allocation or embedding is mature enough in the research community in order to start paving the way towards innovation and commercialization.

For NFV challenges there is still a long path to traverse in order to achieve maturity. Embedding of functions and chaining have attracted most of the attention up to the moment, but there are a lot of considerations to be included. For example, a holistic approach towards embedding and scheduling should be approached in order to enable actual NFV deployments in future network scenarios, such as 5G systems.

PUBLICATIONS

Some ideas and figures in second part of the document, i.e. Contributions, have been based and have previously appeared within the following list of publications.

Book Chapters

- Vicat-Blanc, P., Soudan, S., Figuerola, S., Garcia-Espin, J.A., **Ferrer Riera, J.**, Lopez, E., Buysse, J., Develder, C., Chen, X., Jukan, A., Landi, G., Ciulli, N., Tzanakaki, A., Brogle, M., van Laarhoven, L., Belter, B., Anhalt, F., Escalona, E. et al. Bringing Optical Networks to the Cloud: an Architecture for a Sustainable future Internet. In Domingue, J., Galis, A., Gavras, A., *et al.* editors, The Future Internet, *Future Internet Assembly Book*, volume 6656 of Lecture Notes in Computer Science, pages 307-320. Springer / Heidelbergh. 10.1007/978-3-642-20898-0-22. (2011).

- Figuerola, S., Grasa, E., Garcia-Espin, J.A., **Ferrer Riera, J.**, Reijs, V., Kenny, E., Lemay, M., Savoie, M., Campbell, S., Ruffini, M., O'Mahony, D., Willner, A., and St. Arnaud, B. Bringing Optical Network Control to the User Facilities: Evolution of the User Controlled Light Path Provisioning Paradigm. Cross-Layer Design in Optical Networks edited by Subramaniam, Suresh *et al.*. Volume 15, 2013, pp. 291-323. 10.1007/978-1-4614-5671-1-14. Springer / Heidelbergh.

- Anna Tzanakaki, Markos Anastasopoulos, Bijan Rofoee, Shuping Peng, George Zervas, Reza Nejabati, Dimitra Simeonidou, **Jordi Ferrer Riera**, Eduard Escalona, Giada Landi, Gino Carrozzo, Nicola Ciulli, Kostas Katsalis, Leandros Tassiulas, Thanasis Korakis, Dora Christofi, George Dimostenous, Gert Grammel, Jacopo Panegiani. Converged Wireless Access/Optical Metro Networks in support of Cloud and Mobile Cloud Services deploying SDN principles. Accepted for publication. Springer. To appear 2016.

Journal Articles

- Szegepi, P., **Ferrer Riera, J.**, Garcia-Espin, J.A., Hidell, M., Sjödin, P., Söderman, P., Ruffini, M., O'Mahony, D., Bianco, A., Giraudo, L., Ponce de Leon, M., Power, G., Cervelló-Pastor, C., López, V., Naegele-Jackson, S.: Enabling Future Internet Research: The FEDERICA Case. *Communications Magazine, IEEE*, Special Issue on Future Internet Architectures: Design and Deployment Perspectives. pp 54-61. vol. 49 Issue:7. 0163-6804. 10.1109/MCOM.2011.5936155 (2011).
Impact Factor IF: 3.785 (2011) Quartile: Q1 (Telecommunications Ranking 3 / 79)

- Belter, P., Rodriguez, J., Aznar, J.I., **Ferrer Riera, J.**, Contreras, L.M., Antoniak-Lewandowska, M., Biancani, M., Buysse, J., Develder, C.,

Demchemko, Y., Donadio, P., Simeonidou, D., Nejabati, R., Peng, S., et al.: The GEYSERS optical testbed: A platform for the integration, validation and demonstration of cloud-based infrastructure services, Computer Networks, Available online 3 January 2014, ISSN 1389-1286, http://dx.doi.org/10.1016/j.bjp.2013.12.031.
Impact Factor IF: 1.256 (2014) Quartile: Q2 (Telecommunications Ranking 32 / 77)

- Markos P. Anastasopoulos, Anna Tzanakaki, Bijan Rahimzadeh Rofoee, Shuping Peng, Yan Yan, Dimitra Simeonidou, **Jordi Ferrer Riera**, Eduard Escalona, Giada Landi, Giacomo Bernini, Nicola Ciulli, Kostas Katsalis, Thanasis Korakis. Optical wireless network convergence in support of energy-efficient mobile cloud services. 2015 1387-974X. Photonic Network Communications. V 29 N 3. 10.1007/s11107-015-0494-2 Springer US. 2015-06-01
Impact Factor IF: 0.793 (2014) Quartile: Q3 (Telecommunications Ranking 50 / 77)

Conference Proceedings

- Willner, A., Barz, C., Garcia-Espin, J.A., **Ferrer Riera, J.**, Figuerola, S., and Martini, P.: Harmony - Advance Reservations in Heterogeneous Multi-domain Environments. *Lecture Notes in Computer Science. Networking 2009*. Editors: Frata, L., Schulzrinne, H, Takahashi, Y., and Spaniol, O. Springer Berlin / Heildelberg. pp 871-882. vol. 550. 10.1007/978-3-642-01399-7. (2009)

- Figuerola, S., Garcia-Espin, J.A., **Ferrer Riera, J.**, and Willner, A. Performance Analysis of Harmony: An optical, Multi-domain Network Resource Broker. *Transparent Optical Networks, 2009. ICTON'09. 11th International Conference on*, vol., no., pp1-5, June 28 2009-July 2 2009. DOI: 10.1109/ICTON.2009.518032. (2009).

- Figuerola, S., Garcia-Espin, J.A., **Ferrer Riera, J.**, and Ciulli, N. An Optical network and IT infrastructure virtualisation and provisioning framework. *Optical Internet (COIN), 2010. 9th International Conference on*. 11-14 July 2010. Jeju, Korea (South). 978-1-4244-8221-4. DOI: 10.1109/COIN.2010.5546328. (2010).

- Willner, A., **Ferrer Riera, J.**, Garcia-Espin, J.A., Siguerola, S., De Leenheer, M., and Develder, C. An Analytical Model of the Service Provisioning Time within the Harmony Network Service Plane. IEEE Globecom 2010 Workshop on Management of Emerging Networks and Services (IEEE MENS 2010). December 2010. pp 514-519. Miami, FL, USA. 978-1-4244-8863-6.

- Tzanakaki, A., Anastasopoulos, M., Georgakilas, K., Buysee, J., De Leenheer, M., Develder, C., Peng, S., Nejabati, R., Escalona, E., Simeonidou, D., Ciulli, N., Landi, G., Manfredi, A., Lopez, E. **Ferrer Riera, J.**, Garcia-Espin, J.A., Donadio, P., Parladori, G., and Jimenez, J. Energy Efficiency in integrated IT and Optical Network Infrastructures: The GEYSERS Approach. IEEE INFOCOM 2011

Workshop on Green Communication Networks. pp 343-348. 15-17 April 2011. Shangai, China. 978-1-4244-9920-5/11 .

- Escalona, E., Peng, S., Nejabati, R., Simeonidou, D., Garcia-Espin, J.A., **Ferrer Riera, J.**, Figuerola, S., Landi, G., Ciulli, N., Jimenez, J., Belter, B., Demechemko, Y., de Laat, C., Chen, X., Jukan, A., Soudan, S., Vicat-Blanc, P., Buysse, J., De Leenheer, M., Develder, C., Tzanakaki, A., Robinson, P., Brogle, M., Bohnert, T. Michael. GEYSERS: A Novel Architecture for Virtualisation and Co-provisioning od Dynamic Optical Networks and IT Services. *Future Networks and Mobile Summit 2011*. Warsaw, Poland, 15 - 17 June 2011.

- Tzanakaki, A., Anastasopoulos, M., Georgakilas, K., Buysse, J., De Leenheer, M., Develder, C., Peng, S., Nejabati, R., Escalona, E., Simeonidou, D., Ciulli, N., Landi, G., Brogle, M., Manfredi, A., Lopez, E., **Ferrer Riera, J.**, Garcia-Espin, J.A., Figuerola, S., Donadio, P., Parladori, G., and Jimenez, J. Energy efficiency considerations in integrated IT and optical network resilient infrastructures. (Invited) *Transparent Optical Networks, 2011. ICTON'11. 13th International Conference on*. 978-1-4557-0881-0. 10.1109/ICTON.2011.5971045. August 2011. Stockholm.

- Pages, A., Garcia-Espin, J.A., Spadaro, S., **Ferrer Riera, J.**, Perello, J., and Figuerola, S. Optical Allocation of Virtual Optical Networks for the Future Internet. *Optical Networks Design and Modeling (ONDM), 2012 16th International Conference on*. 17-20 April 2012. pp.1-6.

- Garcia-Espin, J.A., **Ferrer Riera, J.**, Figuerola, S., Ghijsen, M., Demchemko, Y., Buysse, J., De Leenheer, M., Develder, C., Anhalt, F., and Soudan, S. Logical Infrastructure Composition Layer, the GEYSERS Holistic Approach for Infrastructure Virtualisation. *TERENA Networking Conference 12*. 21 - 24 May, Reykjavik, Iceland.

- **Ferrer Riera, J.**, Garcia-Espin, J.A., Figuerola, S., Buysse, J., De Leenheer, M., Develder, C., Peng, S. Converged IT and Optical Network Virtualisation: the last (Clean-)Step Towards Future Internet Infrastructure Management. *Network and Optical Communications (NOC), 2012 17th European Conference on*. 20-22 June, Vilanova i la Geltru, Catalonia. 978-1-4673-0950-9.

- Tzanakaki, A., Anastasopoulos, M., Georgakilas, K. Garcia-Espin, J.A., **Ferrer Riera, J.**, Figuerola, S., Ghijsen, M., Demchemko, Y., De Laat, C., Vicat-Blanc, P., Soudan, S., Anhalt, F., Peng, S., Escalona, E., Nejabati, R., Simeonidou, D. Virtual Infrastructure Planning: the GEYSERS Approach. *Future Network and Mobile Summit 2012*. 4-6 July, Berlin, Germany.

- Garcia-Espin, J.A., **Ferrer Riera, J.**, Figuerola, S., Lopez, E.: A multi-tenancy model based on resource capabilities and ownership for infrastructure management. IEEE International Conference on Cloud

Communications, pp. 682-686. IEEE CloudCom 2012, 2012.

- Bueno, I, Aznar, J., Escalona, E., Garcia-Espin, J.A., **Ferrer Riera, J.**: An OpenNaaS based SDN framework for dynamic QoS control. IEEE Workshop on Software-Defined Networking for Future Network Services, IEEE.vol., no., pp.1,7, 11-13 Nov. 2013

- Anastasopoulos, M., Tzanakaki, A., Zervas, G., Rofoee, B., Nejabati, R., Simeonidou, D., Ciulli, N., Landi, G., **Ferrer Riera, J.**, Garcia-Espin, J.A.: Convergence of Heterogeneous Network and IT Infrastructures in Support of Fixed and Mobile Cloud Services. FNMS 2013 , vol., no., pp.1,9, 3-5 July 2013

- Katsalis, K., Korakis, T., Landi, G., Bernini, G., Rofoee, B., Peng, S., Anastasopoulos, M., Tzanakaki, A., Christofi, D., Georgiades, M., Larsen, R., Ferrer Riera, J., Escalona, E., Garcia-Espin, J.A.: CONTENT project: Considerations towards a Cloud-based Internetworking Paradigm. IEEE Workshop on Software Defined Networking for Future Network Services., vol., no., pp.1,7, 11-13 Nov. 2013.

- Tzanakaki, A., Anastasopoulos, M., Landi, G., Bernini, G., Ciulli, N., Peng, S., Yan, Y., Simeonidou, D., Escalona, E., Garcia-Espin, J.A., **Ferrer Riera, J.**, Katsalis, K.: Wireless and wired network convergence in support of cloud and mobile cloud services: The CONTENT Approach. European Wireless 2014 Conference. Barcelona, May 2014.

- Tzanakaki, A., Anastasopoulos, M., Peng, S., Rofoee, B., Yan, Y., Simeonidou, D., Landi, G., Bernini, G., Ciulli, N., **Ferrer Riera, J.**, Ferrer Riera, J., Escalona, E., Garcia-Espin, J.A., Katsalis, K., Korakis, T.: A Converged Network Architecture for Energy Efficient Mobile Cloud Computing. Optical Network Design and Modelling 2014. ONDM 2014. Stockholm, Sweden. May.

- Tzanakaki, A., Anastasopoulos, M., Peng, S., Rofoee, B., Yan, Y., Simeonidou, D., Landi, G., Bernini, G., Ciulli, N., **Ferrer Riera, J.**, Ferrer Riera, J., Escalona, E., Garcia-Espin, J.A., Katsalis, K., Korakis, T.: Planning of Dynamic Mobile Optical Virtual Network Infrastructures Supporting Cloud Services. European Conference on Networks and Communications 2014. June 2014. Bologna, Italy

PUBLICATIONS

Some ideas and figures in the last part of the dissertation, i.e. Proposal, have been based and have previously appeared within the following list of publications.

Journal Articles

- Tzanakaki, A., Anastasopoulos, M., Georgakilas, K., **Ferrer Riera, J.**, Escalona, E., Garcia-Espin, J.A., Hesselbach, X., Figuerola, S., Landi, G., Bernini, G., Ciulli, N., Peng, S., Nejabati, R., Simeonidou, D., Parniewicz D., Belter, B., and Rodriguez, J.: Planning of Dynamic Virtual Optical Cloud Infrastructures: the GEYSERS Approach. *Communications Magazine, IEEE*, Special Issue on Advances in Network Planning. ol.52, no.1, pp.26,34, January 2014
  Impact Factor IF: 4.007 (2014) Quartile: Q1 (Telecommunications Ranking 3 / 77)
- **Ferrer Riera, J.**, Tzanakaki, A., Antonescu, A., Anastasopoulos, M., García-Espín, J.A., Escalona, E., Peng, S., Landi, G., Bernini, G., Belter, B., Parniewicz, D., Hesselbach, X., Figuerola, S., and Simeonidou, D., Virtual Infrastructures as a service enabling converged optical networks and Data Centres, Optical Switching and Networking, Volume 14, Part 3, August 2014, Pages 197-208, ISSN 1573-4277
  Impact Factor IF: 1.071 (2014) Quartile: Q2 (Telecommunications Ranking 36 / 77)
- Cimmino A, Carapinha J., Xilouris, G., **Jordi Ferrer Riera**, José Bonnet, et al. Requirements and Use Cases System for Virtualized Network Functions Platforms. J Telecommunations Systems and Management 3: 113. (2014) ISSN: 2167-0919 JTSM

Conference Proceedings

- Batalle, J., **Ferrer Riera, J.**, Escalona, E., Garcia-Espin, J.A.: On the implementation of NFV over an OpenFlow Infrastructure: Routing Function Virtualization. IEEE Workshop on Software-Defined Networking for Future Network Services, IEEE. vol., no., pp.1,6, 11-13 Nov. 2013.
- **Ferrer Riera, J.**, Batalle, J., Escalona, E., Garcia-Espin, J.A.: Management of Virtual Infrastructures through OpenNaaS. IEEE International Conference on Smart Communications in Network Technologies. pp 1-5. SACONET 2013, vol.02, no., pp.1,5, 17-19 June 2013.
- **Ferrer Riera, J.**, Mendes, T., Parker, M., Jungnickel, V., Levy, D., Marques, V., Rodrigues, D., Escalona, E., Garcia-Espin, J.A., Walker, S.: Techno-Economics and Cost Analysis of Convergent Access Networks. European Conference on Networks and Communications 2014. June

2014. Bologna, Italy

- Jungnickel, V.; Habel, K.; Parker, M.; Walker, S.; Bock, C.; **Ferrer Riera, J.**; Marques, V.; Levi, D., "Software-defined open architecture for front- and backhaul in 5G mobile networks," in Transparent Optical Networks (ICTON), 2014 16th International Conference on , vol., no., pp.1-4, 6-10 July 2014

- **Ferrer Riera, J.**; Escalona, E.; Parker, M.C.; Walker, S.; Quinlan, T.; Jungnickel, V.; Habel, K.; Marques, V.; Levi, D., "Software-defined wired-wireless access network convergence: The SODALES approach," in Globecom (GC Wkshps), 2014 , vol., no., pp.1522-1527, 8-12 Dec. 2014

- **Ferrer Riera, J.**; Hesselbach, X.; Escalona, E.; Garcia-Espin, J.A.; Grasa, E., "On the complex scheduling formulation of virtual network functions over optical networks," in Transparent Optical Networks (ICTON), 2014 16th International Conference on , vol., no., pp.1-5, 6-10 July 2014

- **Ferrer Riera, J.**; Escalona, E.; Batalle, J.; Grasa, E.; Garcia-Espin, J.A., "Virtual network function scheduling: Concept and challenges," in Smart Communications in Network Technologies (SaCoNeT), 2014 International Conference on , vol., no., pp.1-5, 18-20 June 2014.

- **Ferrer Riera, J.**; Hesselbach, X.; Zotkiewicz, M.; Szostak, M.; Botero, J.-F., "Modelling the NFV forwarding graph for an optimal network service deployment," in Transparent Optical Networks (ICTON), 2015 17th International Conference on , vol., no., pp.1-4, 5-9 July 2015

- Xilouris, G., Kourtis, T., McGrath, M., Riccobene, V., **Ferrer Riera, J.**, Petralia, G., Markakis, E., Pallis, E., Alexiou, G., Gardikis, G., Ramos, A., Bonnet, J., T-NOVA: Network Functions as-a-Service over Virtualised Infrastructures. IEEE Conferene on NFV and SDN. 2015. Demo track.

Part V

APPENDIX

Not I, nor anyone else can travel that road for you.
You must travel it by yourself.
It is not far. It is within reach.
Perhaps you have been on it since you were born, and did not know.
Perhaps it is everywhere - on water and land.
- WALT WHITMAN, Leaves of Grass

A

RESEARCH PROJECTS

Vita brevis breviter in brevi finietur,
Mors venit velociter quae neminem veretur,
Omnia mors perimit et nulli miseretur.
Ad mortem festinamus peccare desistamus.
- (Llibre Vermell de Montserrat)

The work produced within the lifetime of the thesis cannot be seen as a lone ranger in vast the dessert: it is not a stand-alone individual in the research community. Most of the developments, studies, analysis, and activities carried out have been performed within the context of different major research projects in the European community. In order to provide the reader with a complete environment, there exists the requirement to provide a brief description of the different projects where the activities have been contextualized, as well as to identify the most important elements of those projects.

The work produced within the lifetime of the thesis cannot be seen as a lone ranger in the vast dessert

There are three major projects which provide the thesis with a rational context and timeline:

- Generalized Architecture for Dynamic Infrastructure Services (GEYSERS)[a]
- Convergence of Wireless Optical Network in support of Cloud Services (CONTENT) [b]
- T-NOVA: Virtual Network Functions over Virtualized Infrastructures (T-NOVA) [c]

All of them present a common cornerstone upon which the projects have been developed: *virtualization*. Each one of the projects applies the virtualization concept over different entities, e.g. physical resources, network functions; and over different technologies, e.g. software-defined enabled L2 switches, or optical ROADM devices. However, the common leitmotiv behind all of them remains around the virtualization topic, which provides an added-value to all the activities carried out in parallel for the dissertation. The bilateral exchange of information between the projects in the environment and

a http://geysers.eu
b http://content-fp7.eu
c http://t-nova.eu

the activities of the dissertation has been a constant during the whole lifetime.

Additionally, this appendix also contains the description of the Open Network as a Service (OpenNaaS)[d] framework. Open NaaS is an open-source framework, which provides tools for managing the different resources present in any network infrastructure. The software platform was created in order to offer a neutral tool to the different stakeholders comprising heterogeneous, converged networks. It allows them to contribute and benefit from a common network-as-a-service software-oriented stack for both applications and services. The framework has been utilized by the different projects for specific developments and validations, being influenced thus by the outcomes of the dissertation activities.

The rest of the chapter describes more in detail each one of these projects, as well as identifies which are the most valuable parts that have been used as starting point for all the contributions and activities reported later in upcoming chapters.

A.1 THE GEYSERS PROJECT

GEYSERS research activities were focused on addressing the main challenges of the Future Internet such as scalability for a high number of users, high bandwidth connectivity, security mechanisms, convergence of IT and network services, resources partitioning and virtualization, and automated and energy efficient provisioning of network and IT resources. The innovation that GEYSERS brought to those challenges was offered mainly by its novel layering architecture and the new business models that it offered. GEYSERS introduced a new architecture that qualified the inter-working of legacy planes by means of a virtual infrastructure representation layer for network and IT resources and its advanced resource provisioning mechanisms [GERL+10] and [ENJ+10].

The GEYSERS project proposes and explores a key innovative architecture for cloud-oriented virtual infrastructure provisioning, capable of: (i) seamless and coordinated provisioning of virtual infrastructures composed of network and IT resources and (ii) the end-to-end network service delivery that overcomes limitations of the network/-domain segmentation. This is achieved by the adoption of the concepts of IaaS and service oriented networking, enabling infrastructure operators to offer new converged network and IT services as part of the underlying IaaS cloud infrastructure. On the one hand, the service-oriented paradigm and IaaS framework enable flexibility of infrastructure provisioning in terms of configuration, accessibility and availability for the user. On the other hand, the layer-based structure of the GEYSERS architecture enables separation of functional

d http://www.opennaas.org

aspects of each of the entities involved in the converged service provisioning, from the service consumer to the physical ICT infrastructure.

GEYSERS introduced a new architecture that qualified the inter-working of legacy planes by means of a virtual infrastructure representation layer

Figure 60 shows the layering structure of the GEYSERS architecture reference model. Each layer is responsible for the implementation of different functionalities covering full end-to-end service delivery from the service layer to the physical substrate. Central to the GEYSERS architecture and focus of the project are the enhanced NCP, and the novel LICL. The SML represents existing solutions for service management. At the lowest level, the physical infrastructure layer comprises network and IT resources from different Physical Infrastructure Providers. The different resources contained within the lowest level of the architecture depicted in 60 consists of (i) optical network resources, both fiber- and lambda-switching capable, located in the core networks and (ii) IT resources dedicated to computing and storage tasks, located at the edges and interconnected among them through the high-capacity optical network devices.

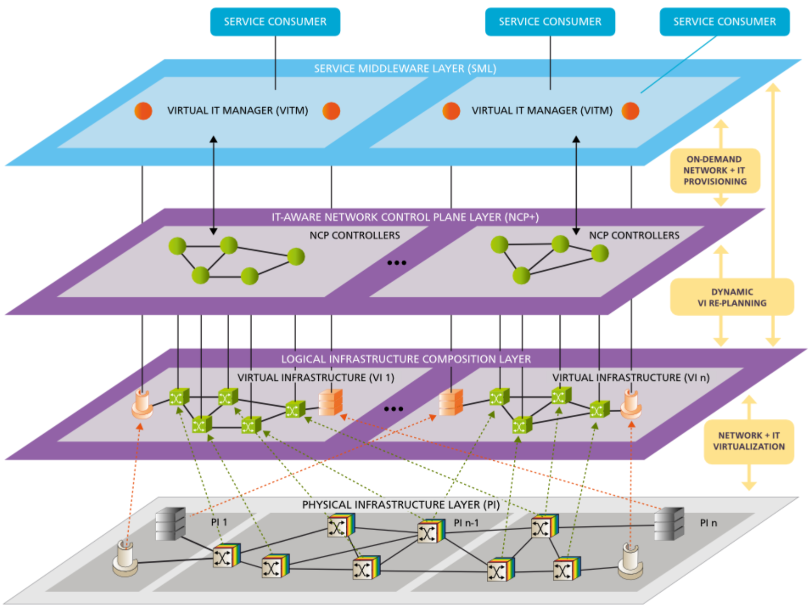

Figure 60: FP7 GEYSERS architecture. Source [GERL+10]

The LICL plays a crucial role in the GEYSERS architecture, as it is responsible for the planning and allocation of virtual infrastructures composed of virtualized network and IT resources [GERF+12]. On the one hand, the LICL is responsible for resource abstraction, resource publishing, VR creation and management, and VR operation. On the other hand, it also deals with VI creation, management and re-planning. Figure 60 depicts the internal representation of the LICL, with several virtual infrastructures composed of different virtual resources – i.e., the green1 and orange boxes – representing virtualized partitions of the physical resources at the bottom level.

The LICL can be seen as the most significant part of theGEYSERS project . The LICL was the layer responsible of providing virtualized resources to the upper layers in the architecture. It manages the physical infrastructure, abstracts it, and creates slices of independent and isolated virtual infrastructures. In the LICL physical devices populating the bottom layer – physical infrastructure layer – are abstracted and partitioned or grouped into virtual resources that can be selected to form the virtual infrastructures. This component holds a uniform semantic resource description model for both network and IT resources, which unifies the abstraction process for the whole substrate. Therefore, at the LICL level, any resource is seen as a generic resource with a set of associated capabilities, such as switching capabilities or computing capabilities. This unified resource description model enables the virtual infrastructure provisioning processes, described in Section 3, to consider both optical networks and data centres in a converged manner. Further details on the unified resource modelling, the so-called Logical Infrastructure Composition Layer - Information Modelling Framework (LICL-IMF), can be found in [GVDHG+13].

On top of the virtual infrastructures, there are the SML and the NCP+. The former is responsible for translating the application requests and SLAs into connectivity specific requests in order to trigger the provisioning procedures at the NCP+ level [BFC+11]. The latter is responsible thus for configuring, and managing virtual resources. These two components are responsible for the coordination of virtualized cloud computing resources and high-capacity network services. The inter-cooperation between the NCP+ and the SML allows the optical network connectivity to be automatically tailored to cloud service dynamics, guaranteeing high performances and reliability and, on the other hand, optimizing the efficiency of the resource provisioning utilization. The communication between theSML and the NCP+, performed through an enhanced User-to-Network Interface (UNI) involves two main procedures. On the one hand, advertisement of virtualized IT resources, that comprises the injection of attached virtual IT resources information (e.g. storage or computing capabilities) into the NCP+. This advertisement enables the utilization of the cloud-related information in the advanced computation processes that take place at the control plane. On the other hand, the interface supports the procedure of requesting coupled IT and network services. Thus, the SML is responsible for requesting the setup, modification and release of enhanced connectivity services. These connection services include the traditional unicast service and advance connectivity services such as the assisted unicast service, the restricted anycast service, and the full anycast service. Detailed information on the NCP+ and SML interactions, as well the advance connectivity services, can be found at [ARB13].

A.1.1 *GEYSERS business roles*

GEYSERS layered architecture enables new service offering paradigms and business models for today's telecom operators, carriers and service providers. As a consequence, new challenges appear on (i) how to model interactions among the entities involved in service provisioning operations and on (ii) how to match them with current infrastructure operation workflows.This is especially critical given the fact that GEYSERS facilitates the appearance of business entities or actors implementing new behaviours, the so-called *roles*, depending on how they interact with or own the infrastructure resources [ENJ+10, BKB+11].

Current business models lack of means to define the interactions and operations of different roles when the resources can be managed differently depending on agreements established by the owner and other entities on the market, so that this entity has granted some rights over the resources but not the whole rights that the economic owner has. As a response, the GEYSERS project defines a novel business model that allows to create different descriptions of the different elements and their relationships. It is the so called RORA model [BKB+11]. It is based in four basic components: (i) resources, that represent the first component model. In the GEYSERS context can be a physical resource, virtual resource or even a virtual infrastructure; (ii) the ownership scheme, which determines the different set of actions that each actor is able to perform over a given resource; (iii) the roles, that represent the minimal entity on the system; and (iv) finally, the actors, who are the actual entities that play one or multiple roles in the market. In GEYSERS, the traditional carrier role is split among PIP, Virtual Infrastructure Provider (VIP), and VIO [VBFC+11].

The PIP is the owner of the physical resources, i.e. both network (optical nodes and links) and IT resources (CPUs, storage and memory), typically associated with the carriers and telecom operators. By leasing virtual resources, a PIP is able to efficiently utilize its infrastructure and obtain an increased benefit from its roll-out, thus achieving a faster return on investment.

The VIP is the infrastructure broker. It offers virtual infrastructures composed of virtual network and IT resources, possibly from several PIPs, according to the requirements of its clients. Being able to provide customized, on-demand virtual infrastructures, the VIP offers more attractive services and increases its competitiveness.

The VIO rents virtual infrastructures and offers unified services over dedicated infrastructures to the end users. This way, the VIO is able to reduce capital expenditure, operational costs and time-to-market. Moreover, the VIO can dynamically adjust the virtual infrastructure according to his needs, thus benefiting from a pay-as-you-grow model.

The VIOs can efficiently operate the rented VI through the enhanced control plane, capable of provisioning on-demand network services bundled with IT resources. This creates new market opportunities for all the different actors: infrastructure providers, infrastructure operators and application providers in order to cooperate in a business model where on-demand services are efficiently offered [BBK+11].

Figure 61 depicts the different service-oriented relationships between the GEYSERS roles, which can be modelled with the below mentioned RORA model.

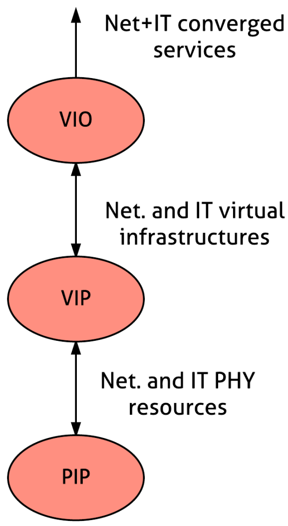

Figure 61: Service-oriented relationships between the GEYSERS roles

A.1.2 *RORA model*

Businesses based on the typical big-sized infrastructure operation usually impose high entry barriers due to the elevated capital costs. To increase competition, by lowering entry barriers, vertical disintegration may be proposed, appearing new business models that include the infrastructure provider and the infrastructure operator as different roles. This evolution can be observed in many different situations, from the railway management and operation to the mobile network service business. The project GEYSERS define a novel business model that allows us to describe the different elements and their relationships in this kind of environments: the RORA Model, which takes its name from the four components it is based on: Resources, Ownership, Roles and Actors.

We can consider that a market is composed by two kinds of elements. The first ones are the active elements, entities with some kind of conscience; as a consequence, their acts intend to lead towards some goal. The second ones are passive elements, which are the object of the actions of the entities and produce some desirable outcomes for these entities. The first elements are defined as the actors in the RORA model, while the second ones are the resources. Actors can perform two different kinds of actions in a market: (1) interactions with other actors, which is usually called a commodities exchange and (2) operations over the resources, which includes from transformation of the resource to its simple usage.

Therefore, resources are the passive elements in the market that are used to generate some final product or service. Resources are described in the RORA model, not only by its definition as concrete element, but also complemented with the description of a set of operations that the actors can perform over it. These operations can range from sell, remove, modify, or even utilize. But these operations are restricted: not everyone can invoke each operation over a resource; it needs to have the correct ownership. Different ownership models are possible in the RORA model; each of them comprising a different set of valid operations over a resource. Additionally ownership may be transferred and/or replicated. If an ownership can be transferred, the owner of the ownership can grant the same type of ownership to somebody else. On the other hand, if the ownership is additionally replicable the owner can duplicate it and grant it to multiple entities. Ownership models can be seen as keys that open the possibility to operate over a resource. These keys can be passed to other entities of the system and some of them can be duplicated, while others cannot.

Usually some common behaviour can be extracted from the different actors, depending on their goal, which is defined as a role in the RORA model. A role is mainly defined by its goal, which requires that the actor performs a set of interactions and operations in order to be achieved. A role may be also restricted to actors with some specific ownership over some resources.

GEYSERS based the RORA model on business scenarios where the vertical disintegration has lead to share a resource substrate among the different entities involved, but each of them has a different set of allowed actions over it. So the first element is the resource, which has to be described in detail and how it is modified through the chain value. Secondly we have the ownership, which determines the actors that are allowed to perform each set of actions over the resource. On a third instance, we have the roles to help us in the chain value description, as they represent the minimal entity on the system. Therefore, the business workflows must be defined in terms of roles and their relationships, both among them and with the resources. Finally, this workflow will be instantiated by actors, who are the actual entities that play one or multiple roles in the market.

Figure 62 and 63 depict the RORA concept. We can visualize the major concepts of the model and the interactions between them, where an actor playing different roles, performing a set of operations over the resources basing on its role. Permissions to operate over the resources are granted by the ownership that an actor has over the resource.

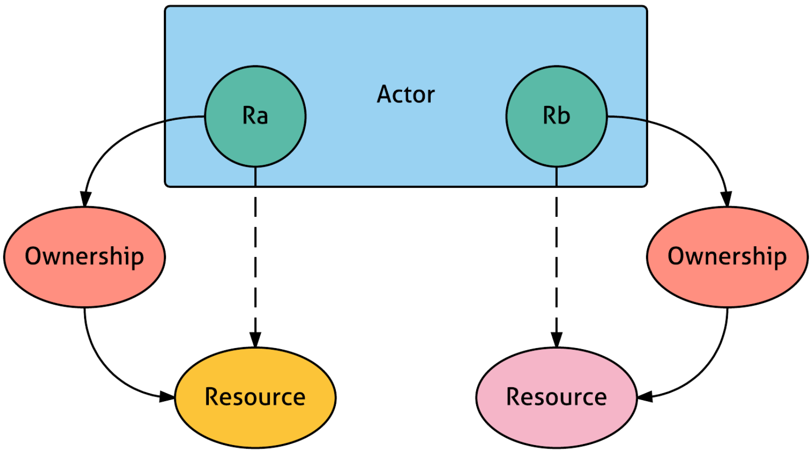

Figure 62: Simplified overview of the RORA model

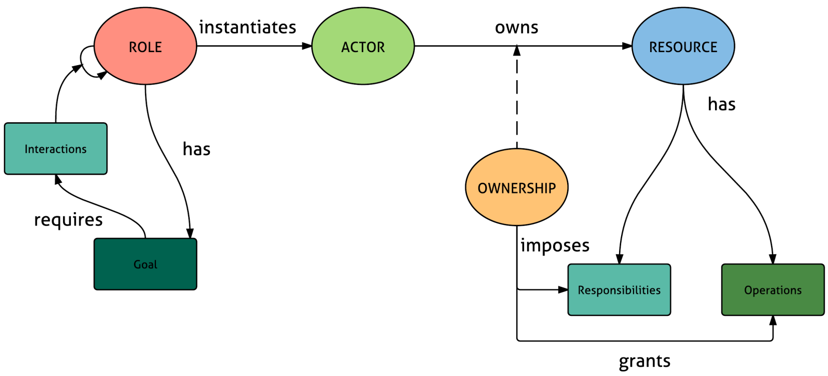

Figure 63: Detailed overview of the RORA model

The RORA model defined within the GEYSERS project becomes of critical importance when defining the virtual infrastructure allocation problem, since it provides the business logic and the basis behind the emergence of all the novel stakeholders involved in the virtualization realm. It was utilized as the business baseline for the technical activities within the dissertation.

A.2 THE CONTENT PROJECT

CONTENT aims at offering a network architecture and overall infrastructure solution to facilitate the deployment of conventional Cloud computing as well as mobile Cloud computing introducing new business models and facilitating new opportunities for a variety of business sectors. The project will focus on a hybrid wireless solution based on WiFi and LTE and a WDM access-metro network with frame-based sub wavelength switching granularity, incorporating active nodes that also support backhauling of the wireless access network and will concentrate on their seamless integration, to provide end-to-end connectivity of IT resources with fixed and mobile users. To support the IaaS paradigm, CONTENT will adopt the concept of physical resources virtualization across the technology domains. One of CONTENT's main objective is to offer a rationalized cost and energy efficient network infrastructure for which it will provide a proof-of-concept demonstration. Work performance, migrate risks and provide resilience against failures and attacks are still ineffective in solving these issues.

CONTENT faces the following objectives:

- Seamless integration of wireless and wired optical access-metro network domains to provide end-to-end connectivity of computational resources with fixed and mobile users.
- A cross-domain and technology virtualization solution allowing the creation and operation of infrastructure slices including subsets of the network and computational physical resources.
- Support of dynamic end-to-end service provisioning across the network segments, offering variable QoS guarantees, throughout the integrated network
- Cost and Energy Efficiency

In architectural terms, the CONTENT infrastructure model aims at providing a technology platform interconnecting geographically distributed computational resources that can support a variety of cloud and mobile cloud services. The proposed architecture comprises an advanced heterogeneous multi-technology network infrastructure integrating optical metro and wireless access network domains interconnecting DCs and adopts the concept of physical resource virtualization across the technology domains involved as shown in Figure 64. In contrast to the existing solutions that use small DCs in the wireless access and large DCs in the core to support mobile and fixed cloud traffic, respectively, the proposed solution relies on a common DC infrastructure fully converged with the broadband wireless access and the metro optical network.

To support the infrastructure as a service paradigm, physical resource virtualization plays a key role in the CONTENT approach and it is enabled by the cross-domain infrastructure management layer of the architectural structure. The project proposed a layered architecture, similar to the GEYSERS layered architecture, with the aim

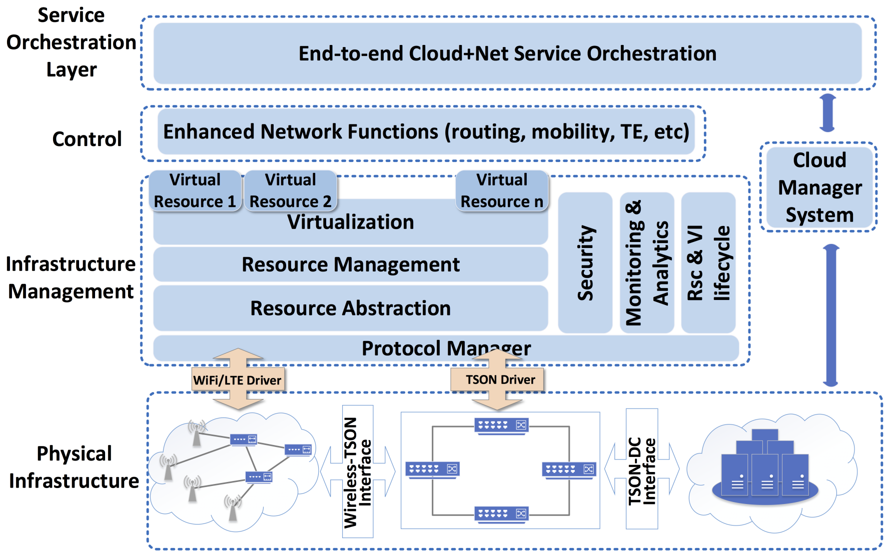

Figure 64: The overall CONTENT layered architecture. Source [KKL+13]

to facilitate the main principles of its novel proposition i.e. cross-technology virtualization in support of optimized, seamless and co-ordinated cloud and mobile cloud service provisioning across heterogeneous network domains.

Heterogeneous Physical Infrastructure Layer: Including a hybrid wireless access network (LTE/WiFi) domain, and an optical metro network domain (TSON) interconnecting geographically distributed data centres, supporting frame-based sub- wavelength switching granularity.

Infrastructure Management Layer: is overall responsible for the management of the network infrastructure and the creation of virtual network infrastructures over the underlying physical resources. This involves functions including resource representation, abstraction, management and virtualization across the heterogeneous network domains. An important feature of the functionalities supported, is orchestrated abstraction of resources across domains, involving information exchange and coordination across domains.

Control Layer: responsible to provision IT and (mobile) connectivity services in the cloud and network domains respectively. The focus of the project is on the network side, where the control layer establishes seamless connectivity across heterogeneous technology domains (wireless access and optical metro) through a coordinated, end-to- end approach to support optimized performance, QoS guarantees as well as resource efficiency and sustainability.

Service Orchestration Layer: responsible for efficient coordination of the cloud and network resources, in order to enable the end-to-end composition and delivery of integrated cloud, mobile cloud and network services in mobile environments supporting the required Quality of Experience (QoE).

A.2.1 *CONTENT business roles*

Equally to the previous business roles defined within the GEYSERS project, CONTENT also defined a set of business roles. In fact, it could be seen as a repetition over the virtualization realm, where a new business role emerges from the brokerage of virtual resources, apart then from the operator of the virtual infrastructure, which does not need to own the physical resources to provide services on top to the end-customers.

Three domains have been identified within the scope of the CONTENT's ecosystem: i) wireless domain (both WiFi and LTE), ii) optical metro domain and iii) IT domain. Taking into account the three different domains we consider the following actors which participate in the CONTENT architecture:

- **PIP**: The administrative owner of the physical infrastructure who has the responsibility of creating the virtual instances of resources on top of it. The PIP is further divided into:
  - Optical Infrastructure Provider (OIP) creates virtual instances of resources on top of its optical network infrastructure.
  - Wireless Infrastructure Provider (WIP) creates virtual instances of resources on top of its wireless network infrastructure.
  - Data Centre Infrastructure Provider (DIP) creates virtual instances of resources on top of its datacentre infrastructure.
- **VIO**: Uses virtualized resources from the Physical Infrastructure Providers on an on-demand basis. It has business legal agreements to access the virtualized resources from one or several Physical Infrastructure Providers. A VIO is responsible for the control and management of its end to end Virtual Infrastructure.
- **Service Provider (SP)**: Responsible to offer value-added services to the end-user and monitor the service provisioned to the end user.

The provisioning of enhanced cloud and mobile cloud services is performed in CONTENT through the implementation of two distinct phases that require interactions among actors and layers: the VI planning, and the VI operation. The former aims to create a new VI: a set of multi- technology virtual resources (i.e. including both wireless and optical resources) are composed and provisioned on top of the physical infrastructure by the PIP upon a request coming from the virtual operator. On the other hand, the VI operation refers to the provisioning of dynamic end-to-end connectivity services and the instantiation of on-demand cloud services to be offered at mobile users. This means that the VI operation phase includes both VI control and converged service orchestration functions.

A.3 THE T-NOVA PROJECT

Virtual Network Functions-as-a-Service over Virtualized Infrastructures (T-NOVA) introduces a novel enabling framework, allowing operators not only to deploy virtualized NFs for their own needs, but also to offer them to their customers, as value-added services. Virtual network appliances (gateways, proxies, firewalls, transcoders, analyzers etc.) can be provided on-demand as-a-Service, eliminating the need to acquire, install and maintain specialized hardware at customers' premises.

In order to facilitate the involvement of diverse actors in the NFV scene and attract new market entrants, T-NOVA establishes a NFV marketplace, in which network services and Functions by several developers can be published and brokered/traded. Via the Marketplace, customers can browse and select the services and virtual appliances which best match their needs, as well as negotiate the associated SLAs and be charged under various billing models. A novel business case for NFV is thus introduced and promoted.

T-NOVA aims at designing and implementing an integrated management architecture, including an Orchestrator platform, for the automated provision, management, monitoring and optimization of Virtualized Network Functions over Network/IT infrastructures. T-NOVA leverages and enhances state-of-the art cloud computing management frameworks for the elastic provision and (re-) allocation of IT resources assigned to the hosting of network functions. It also exploits and extends Software Defined Networking aspects, focusing on the Openflow technology, for efficient management of network resources, including network slicing, traffic redirection and QoS provision.

The T-NOVA architecture, depicted in Figure 65 is hierarchically structured into four architectural layers, each one of them populated by a set of functional components: (i) the NFVI layer includes the physical and virtual nodes (i.e. commodity servers, virtual machines, storage systems, switches, or even routers) on which the services, composed of chained virtual network functions, are actually deployed, as well as the network infrastructure required to connect the different virtual network functions; (ii) the NFVI Management layer encompasses the different management components, namely the Virtual Infrastructure Mapping (VIM) and Transport Network Manager (TNM). Collectively these layers comprise the higher level Infrastructure Virtualization Manager (IVM) functional entity of the T-NOVA system; (iii)

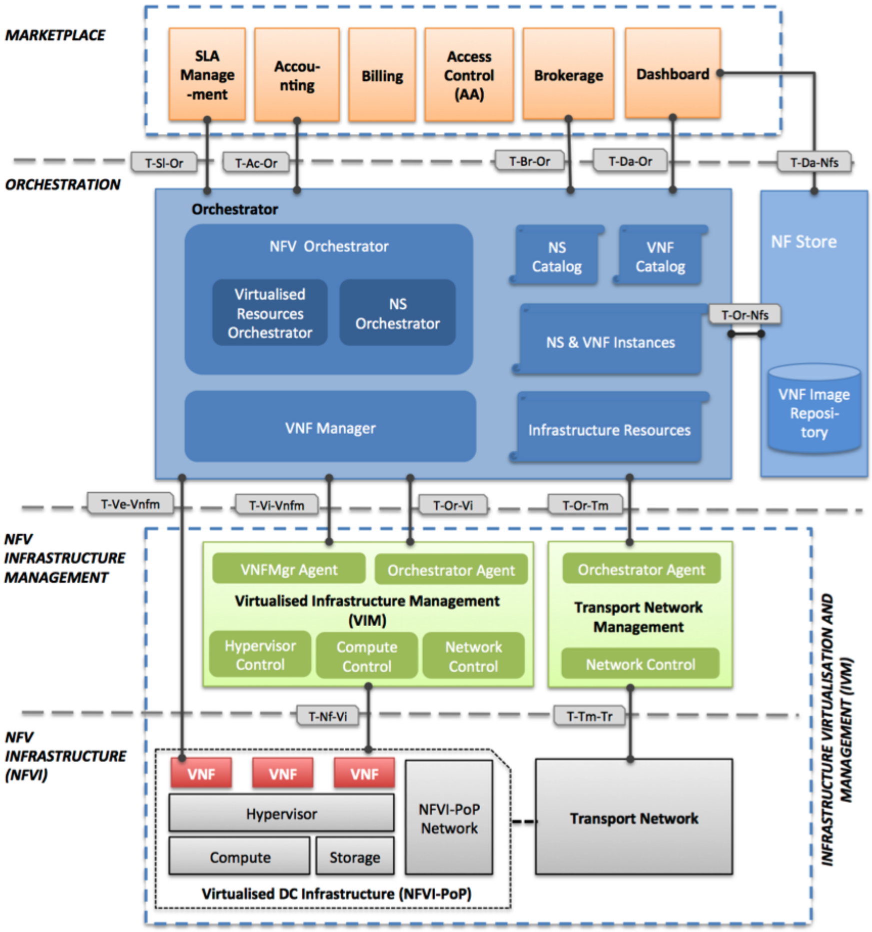

Figure 65: The overall T-NOVA architecture. Source [XTL+14]

the Orchestration layer is based on the Orchestrator component, and also includes the NF Store; and finally (iv) the Marketplace layer contains all the customer-facing modules, which facilitate multi-tenant involvement and implement business-related functionalities.

Orchestrator: The orchestrator is one of the core components of the architecture. It is responsible for NSs and virtual network functions lifecycle management operations over distributed and virtualized network/IT infrastructures. The orchestrator platform is thus focused on addressing two of the most critical issues related to NFV operational environments: (i) automated deployment and configuration of NSs/VNFs; and (ii) management and optimization of networking and IT resources for VNFs hosting. In order to address the complex management processes related with the network services and the virtual network functions, the orchestrator comprises of two major functional blocks. Firstly, the Network Functions Virtualization Orchestrator (NFVO), is responsible for managing operations and procedures relating to the lifecycle of virtualized network service including the networking links that interconnect the VNFs.

The NFVO also manages virtualized infrastructure resource level operations. It coordinates the resource allocation to specific network services and VNF according to the available capacity of the virtualized infrastructures. Secondly, the Virtual Network Function Manager (VNFM), which manages the specific aspects of the VNFs themselves, such as those associated to a given VNF lifecycle. The orchestrator can also deploy and monitor services by jointly managing Wide Area Network (WAN) resources and IT (compute/storage) assets available at the DC located at the NFVI-PoP. The role of the orchestrator extends beyond traditional cloud management, since its scope is not restricted to a single DC; it needs to jointly manage WAN and distributed cloud resources in different interconnected DC in order to couple the basic network connectivity service with added-value NFs.

Infrastructure virtualization management: The concept of virtualization has been a cornerstone in the rapid evolution and adoption of cloud computing. This model of abstracting the physical compute resources into virtual resources has been broadly adopted in the IT domain and is now also being embraced in the networking domain, by introducing VNFs. For network applications such as the deployment of VNFs careful consideration must be given to all elements of the infrastructure environment to ensure the required performance particularly for intensive packets processing workloads or applications that support large numbers of simultaneous connections. In this context the availability of certain features within the CPU, driver performance, or even efficient virtualization of resources can have a significant influence on performance. For this reason, the IVMs domain will comprise of a mixture of nodes (virtual and physical) and will be interoperable with the orchestrator in order to ensure that requirements for the deployment and lifecycle management of VNFs can be carried out in an appropriate and effective manner. As mentioned previously, infrastructure virtualization plays a key role in achieving this vision in the T-NOVA architecture.

A.4 OPEN NETWORK AS A SERVICE

The NaaS model has been brought forward with the OpenNaaS framework for easy, and rapid prototyping and proof casing of distinct NaaS concepts. Open Network as a Service is an open-source framework, which provides tools for managing the different resources present in any network infrastructure. The software platform was created in order to offer a neutral tool to the different stakeholders comprising heterogeneous, converged networks. It allows them to contribute and benefit from a common NaaS software-oriented stack for both applications and services.

OpenNaaS has been developed by an open community under the LGPLv3 license. It is based on a lightweight, abstracted, operational model, which is decoupled from actual vendors' specific details, and is flexible enough to accommodate different designs and orientations. In fact, the OpenNaaS framework provides tools to implement the logic of an SDN-like control and management plane on top of the lightweight abstracted model.

OpenNaaS is an open source platform that provides tools to manage the resources of a network. This software is created to offer a neutral stakeholder to contribute and benefit from a common NaaS software stack oriented for applications and services. The way it is designed allows deploying VNFs inside of it and it offers different useful functionalities.

The elements loaded in OpenNaaS contains a model which stores the information about the resource, and a set of capabilities that allows to access to the data of the model. Furthermore, the design of this NaaS platform allows deploying these capabilities with Web Services and creating a specific management interface for the particular VNFs.

The architecture is built around the resource and services concept. There are different reusable building blocks, which are common to all the extensions and abstractions. In essence, a resource represents a manageable unit inside the NaaS concept. Each resource holds a list of capabilities, which are the list of different actions that can be performed into each resource. OpenNaaS allows to create a software resource (e.g. Devices, Networks, NFs) and manage the offered services.

In fact, the framework can be seen as a resource and services management platform characterized by:

- Secure, robust, and flexible open source framework for an agile and reliable resource and service management
- Orchestrate and compose customized services and applications quickly and hassle-free
- Abstraction and virtualization of resources, functions, and services to provide vendor independent solutions
- Open and accessible interfaces for building tailored visualization platforms
- Automation of processes for an efficient service chaining and OPEX reduction

A.4.1 *Platform concept*

The framework has been built around the concept of *resources* and *services*.

- A resource is a configurable item that provides a set of services

- Services are manageable functions that are offered by one or more resources

The flexibility provided by OpenNaaS and its abstraction capability allows the provisioning of customized services over heterogeneous infrastructure resources.

OpenNaaS is able to manage service and resource interdependencies, enabling the orchestration of composable services and the management of the lifecycle of all resource and service instances within the ecosystem, built around a resource tree. The framework is based on resource abstractions, which provide all the characteristics (i.e. information model) and capabilities (i.e. services) of the given resources. Relationships between resources are modeled by resource trees.

In fact, the resource tree is the inner data structure of the platform. It reflects the available resources and their associated services. At the same time, it is used by various services, e.g. the publication of the REST API.

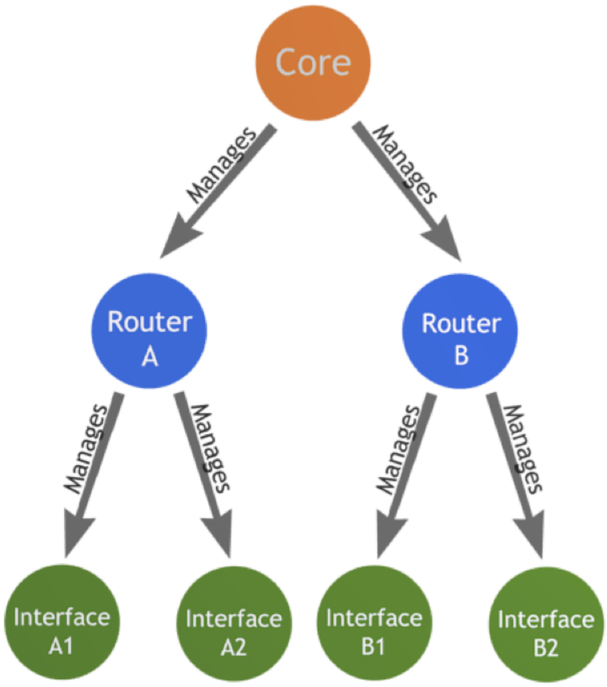

Figure 66: Resource tree example within the network-as-a-service platform

A.5 PROJECTS SUMMARY

It is important to remark again that neither the projects nor the open-source platform are direct work of the dissertation itself. The projects are part of the environment surrounding the research activities within the doctoral thesis. The existence of those international research projects around the topic of our activities demonstrates on the one hand, that the research performed was meaningful, timeliness, and sound in terms of current research happening on an international-wide basis; and on the other hand, that the contributions and proposals made had an impact both on the community and the research projects, due to its tight collaboration. The framework has been utilized by most of the projects in order to develop proof-of-concept prototypes of the different generic architectures.

Relationship between these projects and the research activities of the might be seen as a symbiosis between two different elements (is close and often long-term interaction between two different biological species[e]). In fact, in such symbiotic mutualistic relationship, and while it is clear that the doctoral thesis runs in parallel to the research projects, the thesis has sometimes been fed by the surrounding context of the projects (e.g. in terms of environment), and the projects have been fed by the contributions and proposals of the doctoral activities (e.g. re-planning approaches, or even function scheduling problem definition and challenges identified).

Table 4 summarizes the topics of the projects, the architectural component responsible for such topic, and the contributions from the thesis which mainly impacted in the project and their relationship, as summarized in Chapter 3.

Finally, Figure 67 depicts the timeline of the projects considering the different topics around the virtualization concept described before within Chapters 1 and 2.

e Definition of symbiosis can be found in here `https://en.wikipedia.org/wiki/Glossary_of_ecology` and here `https://en.wikipedia.org/wiki/Symbiosis`

Table 4: Summary of the projects and the bilateral relationship with the dissertation activities

Project	Overall topic	Architectural component	Impact from the thesis
GEYSERS	Net + IT virtualization	Logical Infrastructure Composition Layer	Virtual optical cloud infrastructures allocation, Proposal for dynamic re-planning in support of Cloud services and analysis of the energy consumption of a distributed application on top of the virtual infrastructure, Virtual infrastructure as a service
CONTENT	Wired and wireless convergence	Infrastructure Management Layer	Optical wireless convergence in support of Cloud services, Green virtual infrastructure provisioning
T-NOVA	Network functions virtualization	Orchestrator and infrastructure virtualization manager	Proposal for virtual network function scheduling, NFV challenges identification, models for NSs and VNFs, Initial scheduling solution
OpenNaaS	Generic information and abstraction models, Network-as-a-Service	Abstraction Layer, Network-as-a-Service layer	Virtualization models, virtual infrastructure service provisioning

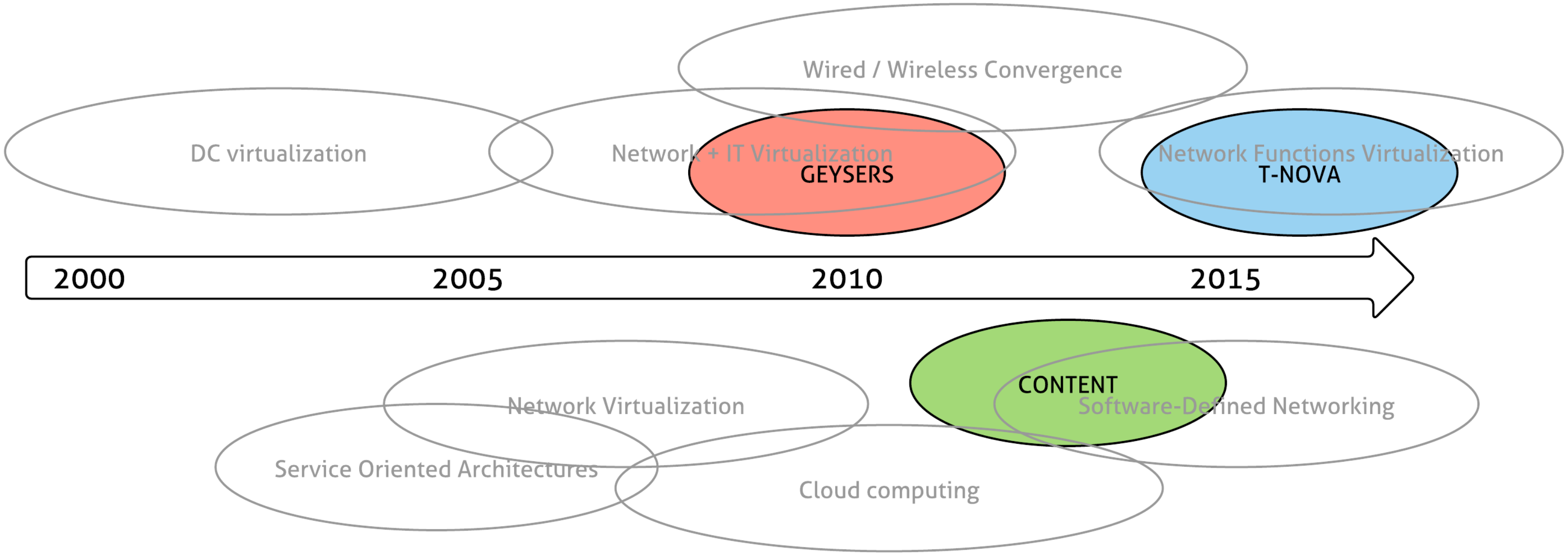

Figure 67: Overall timeline of the projects contextualizing the dissertation

B VIRTUAL INFRASTRUCTURE CLUSTERING

Is trian de'n obair tús a chur.
IRISH PROVERB

This appendix contains the specific formulation upon which our contribution on clustering VI requests was built. The ILP formulation utilized was part of the complete article found in [DLBDM12] and it has been utilized for the contribution within Chapter 5.

B.1 VIRTUAL INFRASTRUCTURE CLUSTERING

The clustering algorithm should group virtual network request that are most similar. Similarity can be based on criteria such as node activity (i.e. nodes where data traffic is generated/received), link overlap (i.e. virtual network requests that have the highest number of overlapping links in the physical topology), etc. Here it is only considered node activity, i.e. their objective is to cluster virtual network requests that have the highest number of active nodes in common. In the following, their solution is presented based on an ILP formulation. There is also a random clustering proposal in order to allow the comparison of both approaches.

The clustering algorithms described below will thus cluster the virtual infrastructure requests in k clusters, after which each virtual infrastructure k is designed based on the aggregate traffic demand matrix $\Lambda^k = \sum_{r \in k} \Lambda^r$.

ILP-based clustering: The following ILP model can provide optimal results for the clustering of virtual network requests, based on node activity. Assume the virtual network requests are represented as traffic matrices Λ^r, and assume we have converted them to active node matrices A^r as follows: $A^r_{ij} = 1$ if $\lambda^r_{ij} \geqslant 0$, 0 otherwise. Introduce binary variables $x^r_k = 1$ if virtual infrastructure request r is partitioned in cluster k, 0 otherwise. Furthermore, let the binary variables $y^i_k = 1$ if node i is active in cluster k, 0 otherwise. Furthermore, integer variables z_k represent the total number of nodes active in a cluster k, while integer variable z is the maximum over all z_k. The objective is to minimize z.

The following constraints must be applied:

- Each cluster contains at least one virtual infrastructure request $\forall k : \sum_r x_k^r \geqslant 1$
- Each demand belongs to one and only one cluster $\forall r : \sum_k x_k^r = 1$
- Acitve nodes are either a source or destination of traffic $\forall i, j, k, r : y_k^i \geqslant A_{ij}^r x_k^r$ and $\forall i, j, k, r : y_k^i \geqslant A_{ij}^r x_k^r$
- Total number of active nodes per cluster $\forall k : z_k = \sum_i y_k^i$.
- Highest number of active nodes in a cluster $\forall k : z \geqslant z_k$.

In other works, it could be also considered the binary linear program, whereby they eliminate variables z_k and z, and introduce objective function $min \sum_k \sum_i y_k^i$. This objective tries to minimize the total number of active nodes over all clusters, but leads to suboptimal results in the scenario considered in Chapter 5. Indeed, results shall be composed of 1 cluster containing $r - (k - 1)$ application requests, while the remaining $k - 1$ clusters contain a single application demand. This corresponds to the lowest number of total active nodes over all clusters, as it is the solution where nodes are activated in as little as clusters as possible. Instead, the proposed objective function integrates load-balancing to effectively strike a balance between control plane scalability and network resource utilization.

Also, additional constraints $\forall k : x_k^{r_1} + x_k^{r_2} \leqslant 1$ may be introduced to enforce isolation between any two application demands r_1 and r_2, which could be necessary based on performance arguments or virtual infrastructure operator policy. For instance, two VIOs of a competing service may choose not to be deployed in the same cluster. This is not considered in the solution analyzed in Chapter 5.

Random Clustering: To demonstrate the need for an intelligent clustering algorithm, results when clustering is performed in a random fashion are also studied. However, the clustering is not completely random, as they must ensure that all clusters contain at least one virtual network request. As such, the clustering algorithm was implemented with a round robin strategy, whereby each cluster is, in turn, assigned a randomly chosen virtual network request. Note that this also ensures that each cluster contains more or less an identical number of elements.

C VIRTUAL NETWORK DESIGN

Luceo Non Uro
(I shall rise not burn)

This appendix contains the description of both the "FullMesh" and "MaxUtil" algorithms, as described in [DLBDM12], and utilized in [RGEF+12, GERF+12].

C.1 FULLMESH

This algorithm minimizes the hop distance in the virtual infrastructure, effectively creating a *full mesh* topology between all active nodes. Implementation of this algorithm is straightforward and detailed below.

First, let $\rho = \frac{\lambda}{\mu}$, then $\mathrm{Erl}(\rho, W) = \frac{\frac{\rho^W}{W!}}{\sum_{i=0}^{W} \frac{\rho^i}{i!}}$ represents the Erlang-B function to calculate the blocking probability of a network link under load ρ and having W wavelengths. The inverse function $\mathrm{Erl}^{-1}(\rho, B)$ then is used to calculate the number of wavelengths necessary to obtain a target blocking probability for a link under load ρ [BKT98].

1. Initialize physical links load to $\rho_l = 0$
2. For each active node pair (i, j) in Λ^k
   a) Perform shortest path routing between i and j on the physical topology
   b) For link l in path: update number of wavelengths $W_l = W_l + \mathrm{Erl}^{-1}(\rho_{ij}^k, B)$

It is expected that the application of this solution will have the lowest number of control planes messages, as every connection only requires signaling over a single link between the source and destination node, as shown in Figure 68. However, as the single hop constraint doe snot allow sharing of resources in the physical network, the resource utilization will consequently suffer.

C.2 MAXUTIL

This second design technique focuses on maximizing utilization by exploiting the effects of statistical multiplexing as much as possible, as depicted in Figures 68 and 69 . The algorithm is outlined below and executed for each virtual infrastructure demand matrix Λ^k.

1. Initialize physical link costs $c_l = c_l^{max} = Erl^{-1}(\rho_{max}, B)$ where $\rho_{max} = \sum_{ij} \rho_{ij}^k$ equals the total load of the virtual network demand matrix[a]
2. Initialize physical links load to $\rho_l = 0$
3. For each active node pair (i, j) in Λ^k
   a) Perform shortest path routing between i and j on the physical topology with link costs c_l
   b) For each link l in path
      1) Update current load on link $\rho_l = \rho_l + \rho_{ij}^k$
      2) Update current cost of link $c_l = c_l^{max} - Erl^{-1}(\rho_l, B)$
4. Calculate the number of wavelengths on each link $W_l = Erl^{-1}(\rho_l, B)$

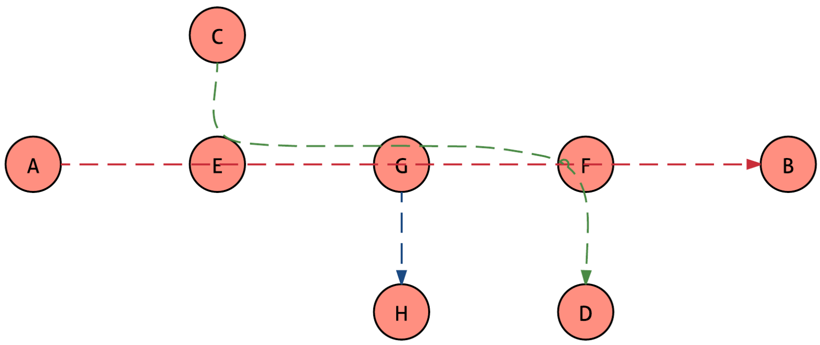

Figure 68: Data plane connections

a i.e. the worst case scenario is where all traffic in the cluster would be routed through a single physical network link

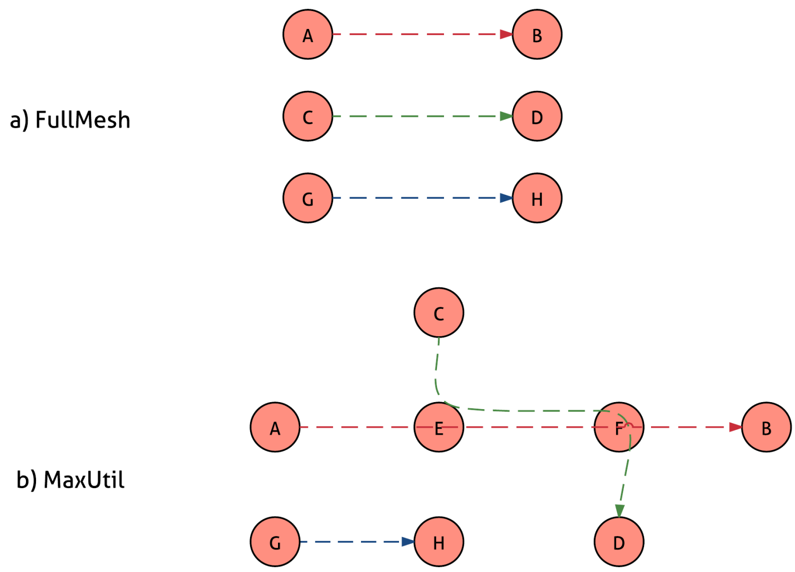

Figure 69: Virtual network design approaches FullMesh (a) and MaxUtil (b) for the virtual network traffic matrix shown in Figure 68. Hope distance in the FullMesh approach is always 1, while it depends on the number of shared links in the MaxUtil case

D VNF EXECUTION EXAMPLES

Fear arises sooner than anything else.
Leonardo Da Vinci

The following appendix contains the tables of the different processing times for each function f_i onto each server s_i considered in the examples of Figures 53 and 54 respectively. The values in **bold** represent the selected servers by the heuristic proposed in the article and the processing time for the corresponding function.

Table 5: Example

Function f	$t(f_i, s_1)$	$t(f_i, s_2)$	$t(f_i, s_3)$	$t(f_i, s_4)$	$t(f_i, s_5)$	$t(f_i, s_6)$
f_1	**2**	2	8	8	3	3
f_2	**7**	7	9	9	8	8
f_3	**2**	2	4	4	7	7
f_4	2	2	**1**	1	5	5
f_5	4	4	**8**	8	3	3
f_6	5	5	1	1	2	**2**
f_7	2	**2**	9	9	7	7
f_8	4	4	7	7	**2**	2
f_9	4	**4**	9	9	7	7
f_{10}	3	3	4	4	**2**	2
f_{11}	7	7	5	5	**2**	2
f_{12}	1	1	4	4	**2**	2
f_{13}	1	**1**	5	5	7	7
f_{14}	7	7	**6**	6	7	7
f_{15}	4	**4**	1	1	4	4
f_{16}	6	6	5	**5**	7	7

Table 6: Table Title

Function f	$t(f_i, s_1)$	$t(f_i, s_2)$	$t(f_i, s_3)$	$t(f_i, s_4)$	$t(f_i, s_5)$	$t(f_i, s_6)$
f_1	6	6	**1**	1	5	5
f_2	7	7	4	4	**3**	3
f_3	10	10	**2**	2	3	3
f_4	6	6	2	2	2	**2**
f_5	3	**3**	5	5	5	5
f_6	**1**	1	6	6	7	7
f_7	1	**1**	3	3	4	4
f_8	5	5	4	**4**	10	10
f_9	4	4	2	**2**	3	3
f_{10}	6	6	7	7	**2**	2
f_{11}	1	**1**	2	2	2	2
f_{12}	7	**7**	10	10	7	7
f_{13}	9	9	**9**	9	9	9
f_{14}	1	**1**	6	6	2	2
f_{15}	5	5	**1**	1	6	6
f_{16}	9	9	1	1	1	**1**
f_{17}	5	5	4	4	6	**6**
f_{18}	10	10	8	8	**1**	1
f_{19}	10	10	2	2	1	**1**
f_{20}	4	4	7	**7**	10	10
f_{21}	5	5	9	9	**1**	1
f_{22}	6	6	5	5	2	**2**
f_{23}	5	5	3	3	**1**	1
f_{24}	**3**	3	5	5	8	8
f_{25}	**6**	6	9	9	8	8
f_{26}	**1**	1	10	10	9	9
f_{27}	4	4	6	6	2	**2**

[3GP] 3GPPP. 3gppp ts23.203 technical specification group services and system aspects.

[ABB+03] L. L. Ashton, E. A. Baker, A. J. Bariska, E. M. Dawson, R. L. Ferziger, S. M. Kissinger, T. A. Menendez, S. Shyam, J. P. Strickland, D. K. Thompson, G. R. Wilcock, and M. W. Wood. Two decades of policy-based storage management for the ibm mainframe computer. *IBM Systems Journal*, 42(2):302 –321, July 2003.

[ABCR66] R. Adair, R. Bayles, L. Comeau, and Creasy R. *A Virtual Machine System for the 360/40*. IBM Cambridge Scientific Center, 1966.

[ACGL04] K. C. Appleby, S. B. Calo, J. R. Giles, and K.-W. Lee. Policy-based automated provisioning. *IBM Systems Journal*, 43(1):121 –135, November 2004.

[AE11a] G. Aljabari and E. Eren. Virtualization of wireless lan infrastructures. In *Intelligent Data Acquisition and Advanced Computing Systems (IDAACS), 2011 IEEE 6th International Conference on*, volume 2, pages 837–841, Sept 2011.

[AE11b] Ghannam Aljabari and Evren Eren. Virtual wlan: Extension of wireless networking into virtualized environments. *International Journal of Computing*, 10(4):322–329, 2011.

[AFG+09] Michael Armbrust, Armando Fox, Rean Griffith, Anthony D. Joseph, Randy H. Katz, Andrew Konwinski, Gunho Lee, David A. Patterson, Ariel Rabkin, Ion Stoica, and Matei Zaharia. Above the clouds: A berkeley view of cloud computing. Technical Report UCB/EECS-2009-28, EECS Department, University of California, Berkeley, Feb 2009.

[AGG+11] G. Auer, V. Giannini, I. Godor, P. Skillermark, M. Olsson, M.A. Imran, D. Sabella, M.J. Gonzalez, C. Desset, and O. Blume. Cellular energy efficiency evaluation framework. In *Vehicular Technology Conference (VTC Spring), 2011 IEEE 73rd*, pages 1–6, May 2011.

[aI57] John Bunyan (author) and Alexander M. Witherspoon (Introduction). *The Pilgrim's Progress*. Pocket Book, 1957.

[AIZ+11] N. Amaya, M. Irfan, G. Zervas, K. Banias, M. Garrich, I. Henning, D. Simeonidou, Y. R. Zhou, A. Lord, K. Smith, V. J. F. Rancano, S. Liu, P. Petropoulos, and D. J. Richardson. Gridless optical networking field trial: flexible spectrum switching, defragmentation and transport of 10g/40g/100g/555g over 620-km field fiber. *Opt. Express*, 19(26):B277–B282, Dec 2011.

[AMZ+11] Norberto Amaya, Irfan Muhammad, Georgios S. Zervas, Reza Nejabati, Dimitra Simeonidou, Yu-Rong Zhou, and Andrew Lord. Experimental demonstration of a gridless multi-granular optical network supporting flexible spectrum switching. In *Optical Fiber Communication Conference*, page OMW3. Optical Society of America, 2011.

[AOD+13] A.-F. Antonescu, A.-M. Oprescu, Y. Demchenko, C. De Laat, and T. Braun. Dynamic optimization of sla-based services scaling rules. In *Cloud Computing Technology and Science (CloudCom), 2013 IEEE 5th International Conference on*, volume 1, pages 282–289, Dec 2013.

[APC08] Markos Anastasopoulos, Athanasios Panagopoulos, and Panayotis Cottis. A distributed routing protocol for providing qos in wireless mesh networks operating above 10ghz. *Wireless Communications and Mobile Computing*, 8(10):1233245, 2008.

[APST05] Thomas Anderson, Larry Peterson, Scott Shenker, and Jonathan Turner. Overcoming the internet impasse through virtualization. *Computer*, 38(4):34–41, April 2005.

[APTM13] Luca Ardito, Giuseppe Procaccianti, Marco Torchiano, and Giuseppe Migliore. Profiling power consumption on mobile devices. *IARIA Journal*, 2013.

[AR02] Amr Awadallah and Mendel Rosenblum. The vMatrix: A Network of Virtual Machine Monitors for Dynamic Content Distribution. In *Proceedings of the 7th International Workshop on Web Content Caching and Distribution (WCW'02)*, 2002.

[ARB12] A.-F. Antonescu, P. Robinson, and T. Braun. Dynamic topology orchestration for distributed cloud-based applications. In *Network Cloud Computing and Applications (NCCA), 2012 Second Symposium on*, pages 116–123, Dec 2012.

[ARB13] A.-F. Antonescu, P. Robinson, and T. Braun. Dynamic sla management with forecasting using multi-objective optimization. In *Integrated Network Management (IM 2013), 2013 IFIP/IEEE International Symposium on*, pages 457–463, May 2013.

[Arm09] Jean Armstrong. Ofdm for optical communications. *J. Lightwave Technol.*, 27(3):189–204, Feb 2009.

[AS13] A. Al-Shabibi. Programmable virtual networks: from network slicing to network virtualization. http://www.slideshare.net/nvirters/virt-july2013meetup,, 2013.

[ATR+15] MarkosP. Anastasopoulos, Anna Tzanakaki, BijanRahimzadeh Rofoee, Shuping Peng, Yan Yan, Dimitra Simeonidou, Giada Landi, Giacomo Bernini, Nicola Ciulli, JordiFerrer Riera, Eduard Escalona, Kostas Katsalis, and Thanasis Korakis. Optical wireless network convergence in support of energy-efficient mobile cloud services. *Photonic Network Communications*, 29(3):269–281, 2015.

[ATS13] M.P. Anastasopoulos, A. Tzanakaki, and D. Simeonidou. Stochastic planning of dependable virtual infrastructures over optical datacenter networks. *Optical Communications and Networking, IEEE/OSA Journal of*, 5(9):968–979, Sept 2013.

[ATZ+13] M.P. Anastasopoulos, A. Tzanakaki, G.S. Zervas, B.R. Rofoee, R. Nejabati, D. Simeonidou, G. Landi, N. Ciulli, J.F. Riera, and J.A. Garcia-Espin. Convergence of heterogeneous network and it infrastructures in support of fixed and mobile cloud services. In *Future Network and Mobile Summit (FutureNetworkSummit), 2013*, pages 1–9, July 2013.

[BAH+09] Jayant Baliga, Robert Ayre, Kerry Hinton, Wayne V. Sorin, and Rodney S. Tucker. Energy consumption in optical ip networks. *Journal Lightwave Technology*, 27(13):2391–2403, Jul 2009.

[BASS11] Theophilus Benson, Aditya Akella, Anees Shaikh, and Sambit Sahu. Cloudnaas: A cloud networking platform for enterprise applications. In *Proceedings of the 2Nd ACM Symposium on Cloud Computing*, SOCC '11, pages 8:1–8:13, New York, NY, USA, 2011. ACM.

[BB15] Michael Beck and Juan Felipe Botero. Coordinated allocation of service function chains. In *2015 IEEE Global Communications Conference: Selected Areas in Communications: Software Defined Networking and Network Functions (GC' 15 - SAC - SDN)*, San Diego, USA, December 2015.

[BBG11] Rajkumar Buyya, James Broberg, and Andrzej Goscinski. *Cloud computing: principles and paradigms*. Wiley, Hoboken, New Jersey, 2011.

[BBK+11] Matteo Biancani, Giorgio Buffa, Pawel Kaczmarek, Marc Brogle, Philip Robinson, Pasquale Donadio, Antonio Cimmino, Javier Jimenez, Noemi Gutierrez, Monika Antoniak-Lewandowska, Lukasz Drzewiecki, Sebastien Soudan, Pascale Vicat-Blanc, Ashwin Gumaste, and Tamal Das. Collected use cases and scenarios. Technical report, GEYSERS EC FP7-ICT-2009.1.1 No. 248657, 2011.

[BCMP75] Forest Baskett, K. Mani Chandy, Richard R. Muntz, and Fernando G. Palacios. Open, closed, and mixed networks of queues with different classes of customers. *J. ACM*, 22(2):248–260, April 1975.

[BDSR10] G. Bhanage, R. Daya, I. Seskar, and D. Raychaudhuri. Vnts: A virtual network traffic shaper for air time fairness in 802.16e systems. In *Communications (ICC), 2010 IEEE International Conference on*, pages 1–6, May 2010.

[BDSZG14] L. Bondan, C.R.P. Dos Santos, and L. Zambenedetti Granville. Management requirements for clickos-based network function virtualization. In *Network and Service Management (CNSM), 2014 10th International Conference on*, pages 447–450, Nov 2014.

[Ber99] D. P. Bertsekas. *Nonlinear Programming*. Athena Scientific, Belmont, MA, 1999.

[BFC+11] T.M. Bohnert, S. Figuerola, N. Ciulli, D. Simeonidou, and P. Vicat-Blanc. Optical networking for cloud computing. In *Optical Fiber Communication Conference and Exposition (OFC/NFOEC), 2011 and the Na-*

tional Fiber Optic Engineers Conference, pages 1–2, March 2011.

[BFJ+10] Marcin Bienkowski, Anja Feldmann, Dan Jurca, Wolfang Kellerer, Gregor Schaffrath, Stefan Schmid, and Joerg Widmer. Competitive analysis for service migration in vnets. In *Proceedings of the Second ACM SIGCOMM Workshop on Virtualized Infrastructure Systems and Architectures*, VISA '10, pages 17–24, New York, NY, USA, 2010. ACM.

[BFREGE13] J. Batalle, J. Ferrer Riera, E. Escalona, and J.A. Garcia-Espin. On the implementation of nfv over an openflow infrastructure: Routing function virtualization. In *Future Networks and Services (SDN4FNS), 2013 IEEE SDN for*, pages 1–6, Nov 2013.

[BKB+11] Giorgio Buffa, Pawel Kaczmarek, Pawel Brzozowski, Piotr Drozda, Marc Brogle, Philip Robinson, Alexandru-Florian Antonescu, Luuk van Laarhoven, Pasquale Donadio, Javier Jimenez, Alejandro Tovar, Noemi Gutierrez, Monika Antoniak-Lewandowska, Augustin Ragon, Fabienne Anhalt, Sebastien Soudan, Jordi Ferrer Riera, Joan A. Garcia-Espin, Ester Lopez, Tamal Das, and Ashutosh Upadhayay. Identification, description, and evaluation of the use case portfolio and potential business models. Technical report, GEYSERS EC FP7-ICT-2009.1.1 No. 248657, 2011.

[BKH+14] Arsany Basta, Wolfgang Kellerer, Marco Hoffmann, Hans Jochen Morper, and Klaus Hoffmann. Applying nfv and sdn to lte mobile core gateways, the functions placement problem. In *Proceedings of the 4th Workshop on All Things Cellular: Operations, Applications, & Challenges*, AllThingsCellular '14, pages 33–38, New York, NY, USA, 2014. ACM.

[BKT98] S. A. Berezner, A. E. Krzesinski, and P. G. Taylor. On the inverse of erlang's function. *J. Appl. Probab.*, 35(1):246–252, 03 1998.

[BLBM14] R. Bolla, C. Lombardo, R. Bruschi, and S. Mangialardi. Dropv2: energy efficiency through network function virtualization. *Network, IEEE*, 28(2):26–32, March 2014.

[BMA+14] Bartosz Belter, Juan Rodriguez Martinez, José Ignacio Aznar, Jordi Ferrer Riera, Luis M. Contreras, Monika Antoniak-Lewandowska, Matteo Biancani, Jens Buysse, Chris Develder, Yuri Demchenko, Pasquale Donadio, Dimitra Simeonidou, Reza Nejabati, Shuping Peng, Drzewiecki, Eduard Escalona, Joan Antoni Garcia Espin, Steluta Gheorghiu, Mattijs Ghijsen, Jakub Gutkowski, Giada Landi, Gino Carrozzo, Damian Parniewicz, Philip Robinson, and Sebastien Soudan. The geysers optical testbed: A platform for the integration, validation and demonstration of cloud-based infrastructure services. *Comput. Netw.*, 61:197–216, March 2014.

[BSE+07] R. Bhatti, A. Samuel, M.Y. Eltabakh, H. Amjad, and A. Ghafoor. Engineering a policy-based system for federated healthcare databases. *Knowledge and Data Engineering, IEEE Transactions on*, 19(9):1288 –1304, September 2007.

[BSMR10] Gautam Bhanage, Ivan Seskar, Rajesh Mahindra, and Dipankar Raychaudhuri. Virtual basestation: Architecture for an open shared wimax framework. In *Proceedings of the Second ACM SIGCOMM Workshop on Virtualized Infrastructure Systems and Architectures*, VISA '10, pages 1–8, New York, NY, USA, 2010. ACM.

[BSR12a] Gautam Bhanage, Ivan Seskar, and Dipankar Raychaudhuri. A service oriented experimentation framework for virtualized wimax systems. In Thanasis Korakis, Hongbin Li, Phuoc Tran-Gia, and Hong-Shik Park, editors, *Testbeds and Research Infrastructure. Development of Networks and Communities*, volume 90 of *Lecture Notes of the Institute for Computer Sciences, Social Informatics and Telecommunications Engineering*, pages 152–161. Springer Berlin Heidelberg, 2012.

[BSR12b] Gautam Bhanage, Ivan Seskar, and Dipankar Raychaudhuri. A virtualization architecture for mobile wimax networks. *SIGMOBILE Mob. Comput. Commun. Rev.*, 15(4):26–37, March 2012.

[BSZ+11] Gautam Bhanage, Ivan Seskar, Yanyong Zhang, Dipankar Raychaudhuri, and Shweta Jain. Experimental evaluation of openvz from a testbed deployment perspective. In Thomas Magedanz, Anastasius Gavras, NguyenHuu Thanh, and JeffryS. Chase, editors, *Testbeds and Research Infrastructures. Development of Networks and Communities*, volume 46 of

Lecture Notes of the Institute for Computer Sciences, Social Informatics and Telecommunications Engineering, pages 103–112. Springer Berlin Heidelberg, 2011.

[BTK14] M. Bagaa, T. Taleb, and A. Ksentini. Service-aware network function placement for efficient traffic handling in carrier cloud. In *Wireless Communications and Networking Conference (WCNC), 2014 IEEE*, pages 2402–2407, April 2014.

[Bun10] John Bunyan. *The Pilgrim Progress*. Dover Thrift Editions, Oxford, 2010.

[Buy09] R. Buyya. Vision, hype, and reality of delivering computing as the fifth utility. In *Proceedings of the 9th IEEE/ACM CCGRID '09*, page 1, May 2009.

[BVSR10] Gautam D. Bhanage, Dipti Vete, Ivan Seskar, and Dipankar Raychaudhuri. Splitap: Leveraging wireless network virtualization for flexible sharing of wlans. In *GLOBECOM*, pages 1–6. IEEE, 2010.

[BYV+09] Rajkumar Buyya, Chee Shin Yeo, Srikumar Venugopal, James Broberg, and Ivona Brandic. Cloud Computing and Emerging IT Platforms: Vision, Hype, and Reality for Delivering Computing as the 5th Utility. *Future Generation Computer Systems*, 25(6):599–616, June 2009.

[BZR11] G. Bhanage, Y. Zhang, and D. Raychaudhuri. Virtual wireless network mapping: An approach to housing mvnos on wireless meshes. In *Personal Indoor and Mobile Radio Communications (PIMRC), 2011 IEEE 22nd International Symposium on*, pages 187–191, Sept 2011.

[CAP+13] N. Cvijetic, M. Angelou, A. Patel, P.N. Ji, and Ting Wang. Defining optical software-defined networks (sdn): From a compilation of demos to network model synthesis. In *Optical Fiber Communication Conference and Exposition and the National Fiber Optic Engineers Conference (OFC/NFOEC), 2013*, pages 1–3, March 2013.

[CB09] N.M.M.K. Chowdhury and R. Boutaba. Network virtualization: state of the art and research challenges. *Communications Magazine, IEEE*, 47(7):20–26, July 2009.

[CB10] N.M. Mosharaf Kabir Chowdhury and Raouf Boutaba. A survey of network virtualization. *Comput. Netw.*, 54(5):862–876, April 2010.

[CCF+05] Matthew Caesar, Donald Caldwell, Nick Feamster, Jennifer Rexford, Aman Shaikh, and Jacobus van der Merwe. Design and implementation of a routing control platform. In *Proceedings of the 2Nd Conference on Symposium on Networked Systems Design & Implementation - Volume 2*, NSDI'05, pages 15–28, Berkeley, CA, USA, 2005. USENIX Association.

[CFP+07] Martin Casado, Michael J. Freedman, Justin Pettit, Jianying Luo, Nick McKeown, and Scott Shenker. Ethane: Taking control of the enterprise. *SIGCOMM Comput. Commun. Rev.*, 37(4):1–12, August 2007.

[CH10] Aaron Carroll and Gernot Heiser. An analysis of power consumption in a smartphone. In *Proceedings of the 2010 USENIX Conference on USENIX Annual Technical Conference*, USENIXATC'10, pages 21–21, Berkeley, CA, USA, 2010. USENIX Association.

[Cha15] The Internet Engineering Task Force Service Function Chaining. Ietf sfc working group. http://datatracker.ietf.org/wg/sfc/charter, 2015.

[Cis12] Cisco. Cisco visual networking index: Global mobile data traffic forecast update, 2012 - 2017, white paper, 2012.

[CLB+12] Jichuan Chang, Kevin T. Lim, John Byrne, Laura Ramirez, and Parthasarathy Ranganathan. Workload diversity and dynamics in big data analytics: Implications to system designers. In *Proceedings of the 2Nd Workshop on Architectures and Systems for Big Data*, ASBD '12, pages 21–26, New York, NY, USA, 2012. ACM.

[CMP+10] Daniel Cordeiro, Grégory Mounié, Swann Perarnau, Denis Trystram, Jean-Marc Vincent, and Frédéric Wagner. Random graph generation for scheduling simulations. In *Proceedings of the 3rd International ICST Conference on Simulation Tools and Techniques*, SIMUTools '10, pages 60:1–60:10, ICST, Brussels, Belgium, Belgium, 2010. ICST (Institute for Computer Sciences, Social-Informatics and Telecommunications Engineering).

[CNS13] M. Channegowda, R. Nejabati, and D. Simeonidou. Software-defined optical networks technology and infrastructure: Enabling software-defined optical network operations [invited]. *Optical Communications and Networking, IEEE/OSA Journal of*, 5(10):A274–A282, Oct 2013.

[Com12] IEEE 802.3 Ethernet Working Group Communication. Ieee 802.3 industry connections ethernet bandwidth assessment. http://www.ieee802.org/3/ad_hoc/bwa/BWA_Report.pdf, 2012.

[con] Open SDN controller. Floodlight. http://floodlight.openflowhub.org.

[Con13] EINS Consortium. Deliverable d8.1: Overview of ict energy consumption. Technical report, EINS EC FP7-2888021, February 2013.

[Cora] Oracle Corp. Oracle data sheet, sun oracle databasemachine. http://www.oracle.com/us/products/database/database-machine-069034.html.

[Corb] Sun Oracle Corp. Oracle data sheet: Sun oracle databasemachine. http://www.oracle.com/us/products/database/.

[Cor09] Oracle Corp. Sun oracle database machine. http://www.oracle.com/us/industries/healthcare/058454.pdf?ssSourceSiteId=ocomjp, 2009.

[Cre07] John Creedy. A phd thesis without tears, 2007.

[Cre08] J.W. Crewell. *Educational Research: Planning, conducting, and evaluating quantitative and qualitative research*. Upper Saddle River: Pearson, 2008.

[CTJ+14] N. Cvijetic, A. Tanaka, P.N. Ji, K. Sethuraman, S. Murakami, and Ting Wang. Sdn and openflow for dynamic flex-grid optical access and aggregation networks. *Lightwave Technology, Journal of*, 32(4):864–870, Feb 2014.

[Dav] Z. Davis. Power consumption and cooling in the data center: survey. http://www.greenbiz.com.

[DCM+11] Ning Deng, Shiyi Cao, Teng Ma, Xiaozhong Shi, Xiaodong Luo, Shuqiang Shen, and Qianjin Xiong. A novel optical burst ring network with optical-layer aggregation and flexible bandwidth provisioning. In *Optical Fiber Communication Conference and Exposition (OFC/NFOEC), 2011 and the National Fiber Optic Engineers Conference*, pages 1–3, March 2011.

[DDLD+12] C. Develder, M. De Leenheer, B. Dhoedt, M. Pickavet, D. Colle, F. De Turck, and P. Demeester. Optical networks for grid and cloud computing applications. *Proceedings of the IEEE*, 100(5):1149–1167, May 2012.

[DFCV14] P. Donadio, G.B. Fioccola, R. Canonico, and G. Ventre. A pce-based architecture for the management of virtualized infrastructures. In *Cloud Networking (CloudNet), 2014 IEEE 3rd International Conference on*, pages 223–228, Oct 2014.

[DKR13] Dmitry Drutskoy, Eric Keller, and Jennifer Rexford. Scalable network virtualization in software-defined networks. *Internet Computing, IEEE*, 17(2):20–27, March 2013.

[DLBDM12] Marc De Leenheer, Jens Buysse, Chris Develder, and Biswanath Mukherjee. Isolation and resource efficiency of virtual optical networks. In *Proc. Int. Conf. Computing, Networking and Communications (ICNC 2012)*, Maui, Hawaii, USA, 30 Jan. – 2 Feb. 2012.

[DLNW13] Hoang T. Dinh, Chonho Lee, Dusit Niyato, and Ping Wang. A survey of mobile cloud computing: architecture, applications, and approaches. *Wireless Communications and Mobile Computing*, 13(18):1587–1611, 2013.

[DPC+10] P. Donadio, G. Parladori, A. Cimino, G. Landi, N. Ciulli, F. Salvestrini, M. Biancani, G. Buffa, M. Brogle, P. Robinson, T. Ginkel, S. Soudan, P. Vicat-Blanc, J.A. Garcia-Espin, J. Ferrer Riera, P. Brzozowsky, M. Antoniak, S. Figuerola, J. Jimenez, A. Upadhyay, T. Das, and A. Gumaste. Identification, analysis, and technical specification of functional and non-functional requirements. Technical report, GEYSERS EC FP7-ICT-2009.1.1 No. 248657, July 2010.

[DPGZ11] Venmani Daniel Philip, Yvon Gourhant, and Djamal Zeghlache. Preliminary analysis of 4g-lte mobile network sharing for improving resiliency and operator differentiation. In JimJames Yonazi, Eliamani

Sedoyeka, Ezendu Ariwa, and Eyas El-Qawasmeh, editors, *e-Technologies and Networks for Development*, volume 171 of *Communications in Computer and Information Science*, pages 73–93. Springer Berlin Heidelberg, 2011.

[DSH+10] A. Doria, J. Hadi Salim, R. Haas, H. Khosravi, W. Wang, L. Dong, R. Gopal, and J. Halpern. Forwarding and Control Element Separation (ForCES) Protocol Specification. RFC 5810 (Proposed Standard), March 2010. Updated by RFCs 7121, 7391.

[Eic08] Dr. Gabriele Eichfelder. *Adaptive Scalarization Methods in Multi-objective Optimization*. Springer Berlin Heidelberg, Berlin, 2008.

[Elb11] H. Elbiaze. Cognitive mechanisms for providing qos in obs networks. In *Transparent Optical Networks (ICTON), 2011 13th International Conference on*, pages 1–4, June 2011.

[EN11] Inc. Enterasys Networks. Data center networking enterasys connectivity and topology design guide, 2011.

[ENJ+10] E. Escalona, R. Nejabati, J. Jimenez, A. Tovar, G. Landi, N. Ciulli, J.A. Garcia-Espin, J. Ferrer Riera, T. Ginkel, P. Robinson, M. Brogle, X. Chen, Sylvana Greco, B. Belter, A. Tzanakaki, P. Donadio, Y. Demchemko, S. Soudan, and C. Develder. Initial geysers architecture and interfaces specification. Technical report, GEYSERS EC FP7-ICT-2009.1.1 No. 248657, September 2010.

[ENJ+11] E. Escalona, R. Nejabati, J. Jimenez, A. Tovar, G. Landi, N. Ciulli, J.A. Garcia-Espin, J. Ferrer Riera, T. Ginkel, P. Robinson, M. Brogle, X. Chen, Sylvana Greco, B. Belter, A. Tzanakaki, P. Donadio, Y. Demchemko, S. Soudan, and C. Develder. Geysers overall architecture interfaces specification and service provisioning workflow. Technical report, GEYSERS EC FP7-ICT-2009.1.1 No. 248657, July 2011.

[EPN+11] E. Escalona, Shuping Peng, R. Nejabati, D. Simeonidou, J.A. Garcia-Espin, J. Ferrer, S. Figuerola, G. Landi, N. Ciulli, J. Jimenez, B. Belter, Y. Demechenko, C. de Laat, Xiaomin Chen, A. Yukan, S. Soudan, P. Vicat-Blanc, J. Buysse, M. De Leenheer, C. Develder, A. Tzanakaki, P. Robinson, M. Brogle, and T.M. Bohnert. Geysers: A novel architecture for virtualization and co-provisioning of dynamic optical networks and it services. In *Future Network Mobile Summit (FutureNetw), 2011*, pages 1–8, June 2011.

[FAPZ11] I. Fajjari, N. Aitsaadi, G. Pujolle, and H. Zimmermann. Vnr algorithm: A greedy approach for virtual networks reconfigurations. In *Global Telecommunications Conference (GLOBECOM 2011), 2011 IEEE*, pages 1–6, Dec 2011.

[FBTB+13] A. Fischer, J.F. Botero, M. Till Beck, H. de Meer, and X. Hesselbach. Virtual network embedding: A survey. *Communications Surveys Tutorials, IEEE*, 15(4):1888–1906, Fourth 2013.

[FGERC10] S. Figuerola, J.A. Garcia-Espin, J.F. Riera, and N. Ciulli. An optical network and it infrastructure virtualisation and provisioning framework. In *Optical Internet (COIN), 2010 9th International Conference on*, pages 1–3, July 2010.

[FGGE+13] Sergi Figuerola, Eduard Grasa, JoanA. Garca-Espn, Jordi Ferrer Riera, Victor Reijs, Eoin Kenny, Mathieu Lemay, Michel Savoie, Scott Campbell, Marco Ruffini, Donal Oahony, Alexander Willner, and BillSt. Arnaud. Bringing optical network control to the user facilities: Evolution of the user-controlled lightpath provisioning paradigm. In Suresh Subramaniam, Mat Brandt-Pearce, Piet Demeester, and Chava Vijaya Saradhi, editors, *Cross-Layer Design in Optical Networks*, volume 15 of *Optical Networks*, pages 291–323. Springer US, 2013.

[FL09] S. Figuerola and M. Lemay. Infrastructure services for optical networks (invited). *J. Opt. Commun. Netw.*, 1(2):A247–A257, Jul 2009.

[Fle12] Grace Fleming. The introductory paragraph: Start with a great first sentence. About.com guide, Retrieved January 2012.

[FMD11] T.K. Forde, I. Macaluso, and L.E. Doyle. Exclusive sharing amp; virtualization of the cellular network. In *New Frontiers in Dynamic Spectrum Access Networks (DySPAN), 2011 IEEE Symposium on*, pages 337–348, May 2011.

[For15] The Internet Engineering Task Force. Ietf. http://www.ietf.org, 2015.

[Fos03] Ian Foster. The grid: Computing without bounds. *Scientific American*, 288(4):78–85, Aril 2003.

[FRBE+14] J. Ferrer Riera, C. Bock, E. Escalona, M.C. Parker, S. Walker, T. Quinlan, V. Jungnickel, K. Habel, V. Marques, and D. Levi. Software-defined wired-wireless access network convergence: The sodales approach. In *Globecom Workshops (GC Wkshps), 2014*, pages 1522–1527, Dec 2014.

[FREB+13] J. Ferrer Riera, E. Escalona, J. Batalle, J.A. Garcia-Espin, and S. Figuerola. Management of virtual infrastructures through opennaas. In *Smart Communications in Network Technologies (SaCoNeT), 2013 International Conference on*, volume 02, pages 1–5, June 2013.

[FREB+14] J. Ferrer Riera, E. Escalona, J. Batalle, E. Grasa, and J.A. Garcia-Espin. Virtual network function scheduling: Concept and challenges. In *Smart Communications in Network Technologies (SaCoNeT), 2014 International Conference on*, pages 1–5, June 2014.

[FRHE+14] J. Ferrer Riera, X. Hesselbach, E. Escalona, J.A. Garcia-Espin, and E. Grasa. On the complex scheduling formulation of virtual network functions over optical networks. In *Transparent Optical Networks (ICTON), 2014 16th International Conference on*, pages 1–5, July 2014.

[FRHZ+15] J. Ferrer Riera, X. Hesselbach, M. Zotkiewicz, M. Szostak, and J.-F. Botero. Modelling the nfv forwarding graph for an optimal network service deployment. In *Transparent Optical Networks (ICTON), 2015 17th International Conference on*, pages 1–4, July 2015.

[FRZ14] Nick Feamster, Jennifer Rexford, and Ellen Zegura. The road to sdn: An intellectual history of programmable networks. *SIGCOMM Comput. Commun. Rev.*, 44(2):87–98, April 2014.

[FSP+12] S. Figuerola, D. Simeonidou, J.F. Palacios, A. Di Giglio, N. Ciulli, J.A. Garcia, R. Nejabati, X. Masip, R. Muoz, G. Landi, M. Yannuzzi, and R. Casellas. Research trends on ict convergence from the caon cluster. In *Transparent Optical Networks (ICTON), 2012 14th International Conference on*, pages 1–4, July 2012.

[fTIS15] Alliance for Telecommunications Industry Solutions. Ait nfv forum. http://www.atis.org/NFV/index.asp, 2015.

[FVA06] A. Farrel, J. P. Vasseur, and J. Ash. RFC 4655: A Path Computation Element (PCE)-Based Architecture. Technical report, IETF, August 2006.

[FWB07] Xiaobo Fan, Wolf-Dietrich Weber, and Luiz Andre Barroso. Power provisioning for a warehouse-sized computer. *SIGARCH Comput. Archit. News*, 35(2):13–23, June 2007.

[G514] SpecPower HP Proliant ML110 G5. Specpower. http://www.spec.org/power_ssj2008/results/res2011q1/power_ssj2008-20110124-00339.html, Online, Apr 2014.

[GC15] Erol Gelenbe and Yves Caseau. The impact of information technology on energy consumption and carbon emissions. *Ubiquity*, 2015(June):1:1–1:15, June 2015.

[GEFRFL12] J.A. Garcia-Espin, J. Ferrer Riera, S. Figuerola, and E. Lopez. A multi-tenancy model based on resource capabilities and ownership for infrastructure management. In *Cloud Computing Technology and Science (CloudCom), 2012 IEEE 4th International Conference on*, pages 682–686, Dec 2012.

[GERF+12] Joan A. Garca-Espn, Jordi Ferrer Riera, Sergi Figuerola, Mattijs Ghijsen, Yuri Demchenko, Jens Buysse, Marc De Leenheer, Chris Develder, Fabienne Anhalt, and Sebastien Soudan. Logical infrastructure composition layer, the geysers holistic approach for infrastructure virtualization. *TERENA Networking Conference*, -, May 2012.

[GERFL12] J.A. Garcia-Espin, J.F. Riera, S. Figuerola, and E. Lopez. A multi-tenancy model based on resource capabilities and ownership for infrastructure management. In *Cloud Computing Technology and Science (CloudCom), 2012 IEEE 4th International Conference on*, pages 682–686, Dec 2012.

[GERL+10] Joan A. Garcia-Espin, Jordi Ferrer Riera, Ester Lopez, Sergi Figuerola, Pasquale Donadio, Giorgio Buffa, Shuping Peng, Eduard Escalona, Sebastien Soudan, Fabienne Anhalt, Philip Robinson, Alexandru-Florian Antonescu, Anna Tzanakaki, Markos Anastasopoulos, Alejandro Tovar, Javier Jimenez, Xiaomin Chen, Canh Ngo, Mattijs Ghijsen, Yuri Demchemko, Giada Landi, Lukasz Lopatowski, Jakub Gutkowski, and Bartosz Belter. Functional description of the logcial infrastructure composition layer. Technical report, GEYSERS EC FP7-ICT-2009.1.1 No. 248657, December 2010.

[GJLY12] O. Gerstel, M. Jinno, A. Lord, and S.J.B. Yoo. Elastic optical networking: a new dawn for the optical layer? *Communications Magazine, IEEE*, 50(2):s12–s20, February 2012.

[GOQSG+10] M.A. Gonzlez-Ortega, Chunming Qiao, A. Suarez-Gonzalez, Xin Liu, and J.-C. Lopez-Ardao. Lobs-h: An enhanced obs with wavelength sharable home circuits. In *Communications (ICC), 2010 IEEE International Conference on*, pages 1–5, May 2010.

[GOSGLALG11] M.A. Gonzlez-Ortega, A. Surez-Gonzlez, J.C. Lpez-Ardao, and C. Lopez-Garcia. Loss differentiation in full wavelength conversion capable obs networks by burst cloning. *Communications Letters, IEEE*, 15(1):85–87, January 2011.

[GTAP12] K.N. Georgakilas, A. Tzanakaki, M. Anastasopoulos, and J.M. Pedersen. Converged optical network and data center virtual infrastructure planning. *Optical Communications and Networking, IEEE/OSA Journal of*, 4(9):681–691, Sept 2012.

[GVDHG+13] Mattijs Ghijsen, Jeroen Van Der Ham, Paola Grosso, Cosmin Dumitru, Hao Zhu, Zhiming Zhao, and Cees De Laat. A semantic-web approach for modeling computing infrastructures. *Comput. Electr. Eng.*, 39(8):2553–2565, November 2013.

[HGL+13] Weigang Hou, Lei Guo, Yejun Liu, Qingyang Song, and Xuetao Wei. Virtual network planning for converged optical and data centers: ideas and challenges. *Network, IEEE*, 27(6):52–58, November 2013.

[HHJ+12] Nikhil Handigol, Brandon Heller, Vimalkumar Jeyakumar, Bob Lantz, and Nick McKeown. Reproducible network experiments using container-based emulation. In *Proceedings of the 8th International Conference on Emerging Networking Experiments and Technologies*, CoNEXT '12, pages 253–264, New York, NY, USA, 2012. ACM.

[Hou14] Yu Cunqian Zong Yue Hou, Weigang. A novel dynamic virtual infrastructure planning for converged optical network and data centers under power outage and evolving recovery. *Optical Switching and Networking*, 14(Part 3):209–216, 2014.

[HSJ+11] Weisheng Hu, Weiqiang Sun, Yaohui Jin, Wei Guo, Hao He, and Lilin Yi. Sub-wavelength switching for future internet. In *Transparent Optical Networks (ICTON), 2011 13th International Conference on*, pages 1–4, June 2011.

[HSMA14] H. Hawilo, A. Shami, M. Mirahmadi, and R. Asal. Nfv: state of the art, challenges, and implementation in next generation mobile networks (vepc). *Network, IEEE*, 28(6):18–26, Nov 2014.

[HSS82] C.W. Haas, D.C. Salerno, and D. Sheinbein. Stored program controlled network: 800 service using spc network capability x2014; network implementation and administrative functions. *Bell System Technical Journal, The*, 61(7):1745–1757, Sept 1982.

[HT13] Christina Hughes and Malcolm Tight. The metaphors we study by: the doctorate as journey or work. *Higher Education Research and Development journal*, 32(5):766 – 775, 2013.

[Hua12] Ivan Huang. The convergence of information and communication technologies gains, 2012.

[HVJ05] Xiaodong Huang, V.M. Vokkarane, and J.P. Jue. Burst cloning: a proactive scheme to reduce data loss in optical burst-switched networks. In *Communications, 2005. ICC 2005. 2005 IEEE International Conference on*, volume 3, pages 1673–1677 Vol. 3, May 2005.

[IBM10] IBM. IBM ILOG CPLEX: high-performance mathematical engine, 2010.

[iG13] Roderic Ortiz i Gisbert. Viatge a itaca. Available online: https://historiata.wordpress.com/2013/05/29/musica-i-poesia-viatge-a-itaca/, 2013.

[Inc13] SAP Inc. Sap standard application benchmarks for 3-tier systems. http://www.sap.com/solutions/benchmark/sd3tier.epx, 2013.

[Itu02] T. Itu. Recommendation G.694.1 - Spectral grids for WDM applications, 2002.

[Jon11] Sreelata Jonnalagedda. Revenue generation in the information era: Opportunities and challenges. *{IIMB} Management Review*, 23(1):51 – 63, 2011.

[JOS+10] M. Jinno, T. Ohara, Y. Sone, A. Hirano, O. Ishida, and M. Tomizawa. Introducing elasticity and adaptation into the optical domain toward more efficient and scalable optical transport networks. In *Kaleidoscope: Beyond the Internet? - Innovations for Future Networks and Services, 2010 ITU-T*, pages 1–7, Dec 2010.

[JS11] David Jenkins and Dale Scholtens. Metro wdm network design evolution: Positioning for the transition to optical meshes, 2011.

[JT04] L. Peterson S. Shenker J. Turner, T. Anderson. Virtualizing the net: A strategy for network de-ossification. http://www.arl.wustl.edu/~jst/talks/hotI-9-04.pdf, 2004.

[JTK+09] M. Jinno, H. Takara, B. Kozicki, Yukio Tsukishima, Y. Sone, and S. Matsuoka. Spectrum-efficient and scalable elastic optical path network: architecture, benefits, and enabling technologies. *Communications Magazine, IEEE*, 47(11):66–73, November 2009.

[KDTR12] Boris Koldehofe, Frank Dürr, Muhammad Adnan Tariq, and Kurt Rothermel. The power of software-defined networking: Line-rate content-based routing using openflow. In *Proceedings of the 7th Workshop on Middleware for Next Generation Internet Computing*, MW4NG '12, pages 3:1–3:6, New York, NY, USA, 2012. ACM.

[KKL+13] K. Katsalis, T. Korakis, G. Landi, G. Bernini, B.R. Rofoee, Shuping Peng, M. Anastasopoulos, A. Tzanakaki, D. Christofi, M. Georgiades, R. Larsen, J. Ferrer Riera, E. Escalona, and J.A. Garcia-Espin. Content project: Considerations towards a cloud-based internetworking paradigm. In *Future Networks and Services (SDN4FNS), 2013 IEEE SDN for*, pages 1–7, Nov 2013.

[KL10] K. Kumar and Yung-Hsiang Lu. Cloud computing for mobile users: Can offloading computation save energy? *Computer*, 43(4):51–56, April 2010.

[KL11] Jae H. Kim and Myung J. Lee. *Green IT: Technologies and Applications*. Springer-Verlag Berlin Heidelberg, 2011.

[KMZR12a] R. Kokku, R. Mahindra, Honghai Zhang, and S. Rangarajan. Nvs: A substrate for virtualizing wireless resources in cellular networks. *Networking, IEEE/ACM Transactions on*, 20(5):1333–1346, Oct 2012.

[KMZR12b] R. Kokku, R. Mahindra, Honghai Zhang, and Sampath Rangarajan. Remove virtualization of a cellular basestation. US Patent, US 2012 0002620 A1, 2012.

[KMZR13] R. Kokku, R. Mahindra, Honghai Zhang, and S. Rangarajan. Cellslice: Cellular wireless resource slicing for active ran sharing. In *Communication Systems and Networks (COMSNETS), 2013 Fifth International Conference on*, pages 1–10, Jan 2013.

[KRV$^+$14] Diego Kreutz, Fernando M. V. Ramos, Paulo Veríssimo, Christian Esteve Rothenberg, Siamak Azodolmolky, and Steve Uhlig. Software-defined networking: A comprehensive survey. *CoRR*, abs/1406.0440, 2014.

[KT11] K.M. Katrinis and A. Tzanakaki. On the dimensioning of wdm optical networks with impairment-aware regeneration. *Networking, IEEE/ACM Transactions on*, 19(3):735–746, June 2011.

[KvdMF14] J. Keeney, S. van der Meer, and L. Fallon. Towards real-time management of virtualized telecommunication networks. In *Network and Service Management (CNSM), 2014 10th International Conference on*, pages 388–393, Nov 2014.

[KW11] M. Klinkowski and K. Walkowiak. Routing and spectrum assignment in spectrum sliced elastic optical path network. *Communications Letters, IEEE*, 15(8):884 –886, august 2011.

[Lan15] Peter Landon. Optical transport sdn, why operators need it? SDN Panel at APRICOT 2015, 2015.

[Laz97] A.A. Lazar. Programming telecommunication networks. *Network, IEEE*, 11(5):8–18, Sep 1997.

[LGT+12] Lei Liu, Hongxiang Guo, T. Tsuritani, Yawei Yin, Jian Wu, Xiaobin Hong, Jintong Lin, and M. Suzuki. Dynamic provisioning of self-organized consumer grid services over integrated obs/wson networks. *Lightwave Technology, Journal of*, 30(5):734–753, March 2012.

[LHM10] Bob Lantz, Brandon Heller, and Nick McKeown. A network in a laptop: Rapid prototyping for software-defined networks. In *Proceedings of the 9th ACM SIGCOMM Workshop on Hot Topics in Networks*, Hotnets-IX, pages 19:1–19:6, New York, NY, USA, 2010. ACM.

[LLK+10] C.F. Lam, Hong Liu, B. Koley, Xiaoxue Zhao, V. Kamalov, and V. Gill. Fiber optic communication technologies: What's needed for datacenter network operations. *Communications Magazine, IEEE*, 48(7):32–39, July 2010.

[LLM96] A.A. Lazar, Koon-Seng Lim, and F. Marconcini. Realizing a foundation for programmability of atm networks with the binding architecture. *Selected Areas in Communications, IEEE Journal on*, 14(7):1214–1227, Sep 1996.

[LM03] Xiaomin Lu and B.L. Mark. A new performance model of optical burst switching with fiber delay lines. In *Communications, 2003. ICC '03. IEEE International Conference on*, volume 2, pages 1365–1369 vol.2, May 2003.

[MAB+08] Nick McKeown, Tom Anderson, Hari Balakrishnan, Guru Parulkar, Larry Peterson, Jennifer Rexford, Scott Shenker, and Jonathan Turner. Openflow: Enabling innovation in campus networks. *SIGCOMM Comput. Commun. Rev.*, 38(2):69–74, March 2008.

[McK09] McKinsey. *Clearing the Air on Cloud Computing*. McKinsey and Co. Analysts, April 2009.

[MCL+03] SophieDe Maesschalck, Didier Colle, Ilse Lievens, Mario Pickavet, Piet Demeester, Christian Mauz, Monika Jaeger, Robert Inkret, Branko Mikac, and Jan Derkacz. Pan-european optical transport networks: An availability-based comparison. *Photonic Network Communications*, 5(3):203–225, 2003.

[MCM11] R. Munoz, R. Casellas, and R. Martinez. Dynamic distributed spectrum allocation in gmpls-controlled elastic optical networks. In *Optical Communication (ECOC), 2011 37th European Conference and Exhibition on*, pages 1–3, Sept 2011.

[MDT14] H. Moens and F. De Turck. Vnf-p: A model for efficient placement of virtualized network functions. In *Network and Service Management (CNSM), 2014 10th International Conference on*, pages 418–423, Nov 2014.

[MEC14] ETSI ISG MEC. Etsi mobile edge computing. http://www.etsi.org/technologies-clusters/technologies/mobile-edge-computing, 2014.

[MG09] P. Mell and T. Grance. The nist definition of cloud computing. Technical Report 15, National Institute of Standards and Technology, 2009.

[MKK14] S. Mehraghdam, M. Keller, and H. Karl. Specifying and placing chains of virtual network functions. In *Cloud Networking (CloudNet), 2014 IEEE 3rd International Conference on*, pages 7–13, Oct 2014.

[MM14] Elisa Maini and Antonio Manzalini. Management and orchestration of virtualized network functions. In *Monitoring and Securing Virtualized Networks and Services - 8th IFIP WG 6.6 International Conference on Autonomous Infrastructure, Management, and Security, AIMS 2014, Brno, Czech Republic, June 30 - July 3, 2014. Proceedings*, pages 52–56, 2014.

[MSG+15] R. Mijumbi, J. Serrat, J. Gorricho, N. Bouten, F. De Turck, and R. Boutaba. Network function virtualization: State-of-the-art and research challenges. *Communications Surveys Tutorials, IEEE*, PP(99):1–1, 2015.

[Muk97] Biswanath Mukherjee. *Optical Communications Networks*. Mcgraw - Hill, 1997.

[Muk06] Biswanath Mukherjee. *Optical WDM Networks*. Springer-Verlag, 2006.

[Mun] K. Mun. Mobile cloud computing challenges. TechZine Magazine.

[Nel10] M.R. Nelson. The next generation internet, e-business, and e-everything. http://www.aaas.org/spp/rd/ch20.pdf, 2010.

[NEPS11] R. Nejabati, E. Escalona, Shuping Peng, and D. Simeonidou. Optical network virtualization. In

Optical Network Design and Modeling (ONDM), 2011 15th International Conference on, pages 1–5, Feb 2011.

[Net11] Intune Networks. Verism ivx 8000, optical packet switch and transport, 2011.

[Net12] Juniper Networks. Cloud ready data center network design guide. http://www.juniper.net/us/en/local/pdf/design-guides/8020014-en.pdf, 2012.

[NFV14] ETSI ISG NFV. Gs nfv 002. network functions virtualization (nfv); architectural framework. http://www.etsi.org/technologies-clusters/technologies/nfv, 2014.

[NFV12a] ETSI ISG NFV. Gs-nfv 003. network functions virtualization (nfv); terminology for main concepts in nfv v1.2.1. http://www.etsi.org/technologies-clusters/technologies/nfv, 2014-12.

[NFV12b] ETSI ISG NFV. Gs nfv-man 001. network functions virtualization (nfv); management and orchestration v1.1.1. http://www.etsi.org/technologies-clusters/technologies/nfv, 2014-12.

[Nic12] Nicira. It is time to virtualize the network. http://nicira.com.en/network-virtualization-platform, 2012.

[NIM+11] K. Nakauchi, K. Ishizu, H. Murakami, A. Nakao, and H. Harada. Amphibia: A cognitive virtualization platform for end-to-end slicing. In *Communications (ICC), 2011 IEEE International Conference on*, pages 1–5, June 2011.

[NMN+14] B.A.A. Nunes, M. Mendonca, Xuan-Nam Nguyen, K. Obraczka, and T. Turletti. A survey of software-defined networking: Past, present, and future of programmable networks. *Communications Surveys Tutorials, IEEE*, 16(3):1617–1634, Third 2014.

[OEC02] OECD. Frascati manual: proposed standard practice for surveys on research and experimental development, 6th edition. http://www.oecd.org/sti/frascatimanual, 2002.

[O'M96] M.J. O'Mahony. Results from the cost 239 project. ultra-high capacity optical transmission networks.

In *Optical Communication, 1996. ECOC '96. 22nd European Conference on*, volume 2, pages 11–18 vol.2, Sept 1996.

[ONF12] White paper Open Networking Foundation. Software-defined networking: The new norm for networks. www.onf.org, 2012.

[ONF14] ONF Open Networking Foundation. Openflow-enabled transport sdn, 2014.

[Pac97] Gyula Paczolay. *European Proverbs in 55 languages*. DeProverbio.com, 1997.

[PCC+08] P. Pedroso, D. Careglio, R. Casellas, M. Klinkowski, and J. Sole-Pareta. An interoperable gmpls/obs control plane: Rsvp and ospf extensions proposal. In *Communication Systems, Networks and Digital Signal Processing, 2008. CNSDSP 2008. 6th International Symposium on*, pages 418–422, July 2008.

[PCM09] S. Perez, J.M. Cabero, and E. Miguel. Virtualization of the wireless medium: A simulation-based study. In *Vehicular Technology Conference, 2009. VTC Spring 2009. IEEE 69th*, pages 1–5, April 2009.

[PG74] Gerald J. Popek and Robert P. Goldberg. Formal requirements for virtualizable third generation architectures. *Commun. ACM*, 17(7):412–421, July 1974.

[Pla11] Plato. *The Republic*. Harlan Davidson, trad. Richard W. Sterling and William C. Scott, 2011.

[PNA+11] Shuping Peng, R. Nejabati, S. Azodolmolky, E. Escalona, and D. Simeonidou. An impairment-aware virtual optical network composition mechanism for future internet. In *Optical Communication (ECOC), 2011 37th European Conference and Exhibition on*, pages 1–3, Sept 2011.

[PPK+09] B. Pfaff, J. Pettit, T. Koponen, K. Amidon, M. Casado, and S. Shenker. Extending networking into the virtualization layer. In *Proc. of workshop on Hot Topics in Networks (HotNets-VIII)*, 2009.

[PPP07] Georgios Papadimitriou, Chrisoula Papazoglou, and Andreas Pomportsis. *Optical Switching*. Wiley-Interscience, 2007.

[PPS+12] A. Pages, J. Perello, S. Spadaro, J.A. Garcia-Espin, J. Ferrer Riera, and S. Figuerola. Optimal allocation of virtual optical networks for the future internet. In *Optical Network Design and Modeling (ONDM), 2012 16th International Conference on*, pages 1 –6, april 2012.

[PPSJ12] A. Pages, J. Perell, S. Spadaro, and G. Junyent. Strategies for virtual optical network allocation. *Communications Letters, IEEE*, 16(2):268–271, February 2012.

[PS06] S. Paul and S. Seshan. Virtualization and slicing of wireless networks. GENI Design Document 06-17, Wireless working group, 2006.

[PSCJ09] J. Perell, S. Spadaro, J. Comellas, and G. Junyent. Burst contention avoidance schemes in hybrid gmpls-enabled obs/ocs optical networks. In *Optical Network Design and Modeling, 2009. ONDM 2009. International Conference on*, pages 1–6, Feb 2009.

[QWL06] Chunming Qiao, Wei Wei, and Xin Liu. Extending generalized multiprotocol label switching (gmpls) for polymorphous, agile, and transparent optical networks (paton). *Communications Magazine, IEEE*, 44(12):104–114, Dec 2006.

[QY99] Chunming Qiao and Myungsik Yoo. Optical burst switching (obs) - a new paradigm for an optical internet. *J. High Speed Netw.*, 8(1):69–84, March 1999.

[Rah09] Muntasir Raihan Rahman. Mechanism design for network virtualization, 2009.

[Rea12] Bijan R. Rofoee and et al. Demonstration of low latency intra/inter data-centre heterogeneous optical sub-wavelength network using extended gmpls-pce control-plane. *Optical Express*, 21, 2012.

[RGEF+12] J.F. Riera, J.A. Garcia-Espin, S. Figuerola, J. Buysse, M. De Leenheer, C. Develder, and Shuping Peng. Converged it and optical network virtualisation: The last (clean-)step towards the future internet infrastructure management. In *Networks and Optical Communications (NOC), 2012 17th European Conference on*, pages 1–5, June 2012.

[RKS02] C. Rensing, M. Karsten, and B. Stiller. Aaa: a survey and a policy-based architecture and framework. *Network, IEEE*, 16(6):22 – 27, November 2002.

[RTA+14] Jordi Ferrer Riera, Anna Tzanakaki, Alexandru-Florian Antonescu, Markos Anastasopoulos, Joan A. Garca-Espn, Eduard Escalona, Shuping Peng, Giada Landi, Giacomo Bernini, Bartosz Belter, Damian Parniewicz, Xavier Hesselbach, Sergi Figuerola, and Dimitra Simeonidou. Virtual infrastructures as a service enabling converged optical networks and data centres. *Optical Switching and Networking*, 14, Part 3:197 – 208, 2014. SI: Optimization and Application in Converged Optical and Data Center Networks.

[SAGB14] Z. Sanaei, S. Abolfazli, A. Gani, and R. Buyya. Heterogeneity in mobile cloud computing: Taxonomy and open challenges. *Communications Surveys Tutorials, IEEE*, 16(1):369–392, First 2014.

[SB08] Joachim Sachs and Stephan Baucke. Virtual radio: A framework for configurable radio networks. In *Proceedings of the 4th Annual International Conference on Wireless Internet*, WICON '08, pages 61:1–61:7, ICST, Brussels, Belgium, Belgium, 2008. ICST (Institute for Computer Sciences, Social-Informatics and Telecommunications Engineering).

[SCB13] Fady Samuel, Mosharaf Chowdhury, and Raouf Boutaba. Polyvine: policy-based virtual network embedding across multiple domains. *Journal of Internet Services and Applications*, 4(1), 2013.

[SCFY96] R.S. Sandhu, E.J. Coyne, H.L. Feinstein, and C.E. Youman. Role-based access control models. *Computer*, 29(2):38 –47, February 1996.

[Sch12] D.A. Schupke. Multilayer and multidomain resilience in optical networks. *Proceedings of the IEEE*, 100(5):1140–1148, May 2012.

[SCH+14] M. Satyanarayanan, Zhuo Chen, Kiryong Ha, Wenlu Hu, W. Richter, and P. Pillai. Cloudlets: at the leading edge of mobile-cloud convergence. In *Mobile Computing, Applications and Services (MobiCASE), 2014 6th International Conference on*, pages 1–9, Nov 2014.

[SGY+10] Rob Sherwood, Glen Gibb, Kok-Kiong Yap, Guido Appenzeller, Martin Casado, Nick McKeown, and Guru Parulkar. Can the production network be the testbed? In *Proceedings of the 9th USENIX Conference on Operating Systems Design and Implementa-*

tion, OSDI'10, pages 1–6, Berkeley, CA, USA, 2010. USENIX Association.

[SHSR08] S. Singhal, G. Hadjichristofi, I. Seskar, and D. Raychaudhri. Evaluation of uml based wireless network virtualization. In *Next Generation Internet Networks, 2008. NGI 2008*, pages 223–230, April 2008.

[Shu08] Martyn Shuttleworth. Definition of research. Explorable, from `explorable.com`, 2008.

[SLX12] S. Shetty, N. Luna, and Kaiqi Xiong. Assessing network path vulnerabilities for secure cloud computing. In *Communications (ICC), 2012 IEEE International Conference on*, pages 5548–5552, June 2012.

[SN05] J.E. Smith and R. Nair. The architecture of virtual machines. *Computer*, 38(5):32–38, May 2005.

[Son13] Haoyu Song. Protocol-oblivious forwarding: Unleash the power of sdn through a future-proof forwarding plane. In *Proceedings of the Second ACM SIGCOMM Workshop on Hot Topics in Software Defined Networking*, HotSDN '13, pages 127–132, New York, NY, USA, 2013. ACM.

[SRGE+11] P. Szegedi, J.F. Riera, J.A. Garcia-Espin, M. Hidell, P. Sjodin, P. Soderman, M. Ruffini, D. O'Mahony, A. Bianco, L. Giraudo, M.P. De Leon, G. Power, C. Cervello-Pastor, V. Lopez, and S. Naegele-Jackson. Enabling future internet research: the federica case. *Communications Magazine, IEEE*, 49(7):54–61, July 2011.

[SYK+14] Wenyu Shen, M. Yoshida, T. Kawabata, K. Minato, and W. Imajuku. vconductor: An nfv management solution for realizing end-to-end virtual network services. In *Network Operations and Management Symposium (APNOMS), 2014 16th Asia-Pacific*, pages 1–6, Sept 2014.

[SYMI15] Wenyu Shen, M. Yoshida, K. Minato, and W. Imajuku. vconductor: An enabler for achieving virtual network integration as a service. *Communications Magazine, IEEE*, 53(2):116–124, Feb 2015.

[TAG+11a] A. Tzanakaki, M. Anastasopoulos, K. Georgakilas, J. Buysse, M. De Leenheer, C. Develder, S. Peng, R. Nejabati, E. Escalona, D. Simeonidou, N. Ciulli,

G. Landi, M. Brogle, A. Manfredi, E. Lopez, J. Ferrer Riera, J.A. Garcia-Espin, P. Donaldio, G. Parladori, J. Jimenez, A. Tovar De Duenyas, P. Vicat-Blanc, J. van der Ham, C. de Laat, M. Ghijsen, B. Belter, A. Binczewski, and M. Antoniak-Lewandowska. Energy efficiency considerations in integrated it and optical network resilient infrastructures. In *Transparent Optical Networks (ICTON), 2011 13th International Conference on*, pages 1–4, June 2011.

[TAG+11b] A. Tzanakaki, M. Anastasopoulos, K. Georgakilas, J. Buysse, M. De Leenheer, C. Develder, Shuping Peng, R. Nejabati, E. Escalona, D. Simeonidou, N. Ciulli, G. Landi, M. Brogle, A. Manfredi, E. Lopez, J.F. Riera, J.A. Garcia-Espin, P. Donadio, G. Parladori, and J. Jimenez. Energy efficiency in integrated it and optical network infrastructures: The geysers approach. In *Computer Communications Workshops (INFOCOM WKSHPS), 2011 IEEE Conference on*, pages 343–348, April 2011.

[TAG+12] A. Tzanakaki, M.P. Anastasopoulos, K. Georgakilas, J.A. Garcia-Espin, J. Ferrer Riera, S. Figuerola, M. Ghijsen, Y. Demchenko, C.T.A.M. De Laat, P. Vicat-Blanc, S. Soudan, F. Anhalt, S. Peng, E. Escalona, R. Nejabati, and D. Simeonidou. Virtual infrastructure planning: The geysers approach. In *Future Network Mobile Summit (FutureNetw), 2012*, pages 1–9, July 2012.

[TAG13] A. Tzanakaki, M.P. Anastasopoulos, and K.N. Georgakilas. Dynamic virtual optical networks supporting uncertain traffic demands [invited]. *Optical Communications and Networking, IEEE/OSA Journal of*, 5(10):A76–A85, Oct 2013.

[TAG+14] A. Tzanakaki, M. Anastasopoulos, K. Georgakilas, G. Landi, G. Bernini, N. Ciulli, J.F. Riera, E. Escalona, J.A. Garcia-Espin, X. Hesselbach, S. Figuerola, Shuping Peng, R. Nejabati, D. Simeonidou, D. Parniewicz, B. Belter, and J. Rodriguez Martinez. Planning of dynamic virtual optical cloud infrastructures: The geysers approach. *Communications Magazine, IEEE*, 52(1):26–34, January 2014.

[TAL+14] Anna Tzanakaki, Markos Anastasopoulos, Giada Landi, Giacomo Bernini, Nicola Ciulli, Shuping

Peng, B. Rofoee, Yan Yan, Yan Yan, Dimitra Simeonidou, J.F. Riera, Eduard Escalona, Joan A. Garcia-Espin, Kostas Katsalis, and T. Korakis. Wireless and wired network convergence in support of cloud and mobile cloud services: The content approach. In *European Wireless 2014; 20th European Wireless Conference; Proceedings of*, pages 1–7, May 2014.

[TAP+14] A. Tzanakaki, M.P. Anastasopoulos, S. Peng, B. Rofoee, Y. Yan, D. Simeonidou, G. Landi, G. Bernini, N. Ciulli, J.F. Riera, E. Escalona, J.A. Garcia-Espin, K. Katsalis, and T. Korakis. A converged network architecture for energy efficient mobile cloud computing. In *Optical Network Design and Modeling, 2014 International Conference on*, pages 120–125, May 2014.

[Tel14] British Telecom. What is nfv? http://www.globalservices.bt.com/uk/en/point-of-view/nfv, 2014.

[TGG+12] Amin Tootoonchian, Sergey Gorbunov, Yashar Ganjali, Martin Casado, and Rob Sherwood. On controller performance in software-defined networks. In *Proceedings of the 2Nd USENIX Conference on Hot Topics in Management of Internet, Cloud, and Enterprise Networks and Services*, Hot-ICE'12, pages 10–10, Berkeley, CA, USA, 2012. USENIX Association.

[Tho15] Pat Thomson. Is the phd a journey? http://patthomson.net/2015/03/23/is-the-phd-a-journey/, 2015.

[TKP+11] Anna Tzanakaki, Kostas Katrinis, Tanya Politi, Alex Stavdas, Mario Pickavet, Peter VanDaele, Dimitra Simeonidou, Mike O'Mahony, Slavisa Aleksic, Lena Wosinska, and Paolo Monti. Power considerations towards a sustainable pan-european network. In *Optical Fiber Communication Conference*, page JWA061. Optical Society of America, 2011.

[TKS+12] Shiao-Li Tsao, Chih-Chen Kao, I. Suat, Yuchen Kuo, Yi-Hsin Chang, and Cheng-Kun Yu. Powermemo: A power profiling tool for mobile devices in an emulated wireless environment. In *System on Chip (SoC), 2012 International Symposium on*, pages 1–5, Oct 2012.

[Ton14] Abel Tong. Why gmpls is not carrier sdn, 2014.

[TR112] Release 2.0 TR139, Service Delivery Framework. Tr139. http://www.tmforum.org, Retrieved April 2012.

[TS06] Andrew S. Tanenbaum and Maarten van Steen. *Distributed Systems: Principles and Paradigms (2Nd Edition)*. Prentice-Hall, Inc., Upper Saddle River, NJ, USA, 2006.

[TSS+97] D.L. Tennenhouse, J.M. Smith, W.D. Sincoskie, D.J. Wetherall, and G.J. Minden. A survey of active network research. *Communications Magazine, IEEE*, 35(1):80–86, Jan 1997.

[TT05] Jon Turner and David Taylor. Diversifying the internet. In *In Proc. IEEE GLOBECOM*, pages 755–760, 2005.

[VBFC+11] Pascale Vicat-Blanc, Sergi Figuerola, Xiaomin Chen, Giada Landi, Eduard Escalona, Chris Develder, Anna Tzanakaki, Yuri Demchenko, Joan Garcia Espin, Jordi Ferrer Riera, Ester Lopez, Sebastien Soudan, Jens Buysse, Admela Jukan, Nicola Ciulli, Marc Brogle, Luuk van Laarhoven, Bartosz Belter, et al. Bringing optical networks to the cloud: An architecture for a sustainable future internet. In John Domingue, Alex Galis, et al., editors, *The Future Internet*, volume 6656 of *Lecture Notes in Computer Science*, pages 307–320. Springer Berlin / Heidelberg, 2011. 10.1007/978-3-642-20898-0-22.

[Ver11] Dominique Verchere. Cloud computing over telecom network. In *Optical Fiber Communication Conference and Exposition/National Fiber Optic Engineers Conference (OFC/NFOEC)*, 2011.

[VHLL+14] Ward Van Heddeghem, Sofie Lambert, Bart Lannoo, Didier Colle, Mario Pickavet, and Piet Demeester. Trends in worldwide ict electricity consumption from 2007 to 2012. *Comput. Commun.*, 50:64–76, September 2014.

[Vir15] The Internet Research Task Force Network Functions Virtualization. Irtf nfv research group nfvrg. https://irtf.org/nfvrg, 2015.

[VJS02] V.M. Vokkarane, J.P. Jue, and S. Sitaraman. Burst segmentation: an approach for reducing packet loss in optical burst switched networks. In *Communications, 2002. ICC 2002. IEEE International Conference on*, volume 5, pages 2673–2677 vol.5, May 2002.

[VLM+09] Vytautas Valancius, Nikolaos Laoutaris, Laurent Massoulié, Christophe Diot, and Pablo Rodriguez. Greening the internet with nano data centers. In *Proceedings of the 5th International Conference on Emerging Networking Experiments and Technologies*, CoNEXT '09, pages 37–48, New York, NY, USA, 2009. ACM.

[VLZJ11] A. Vahdat, Hong Liu, Xiaoxue Zhao, and C. Johnson. The emerging optical data center. In *Optical Fiber Communication Conference and Exposition (OFC/NFOEC), 2011 and the National Fiber Optic Engineers Conference*, pages 1–3, March 2011.

[VMB15] P. Veitch, M.J. McGrath, and V. Bayon. An instrumentation and analytics framework for optimal and robust nfv deployment. *Communications Magazine, IEEE*, 53(2):126–133, Feb 2015.

[VMTP11] F. Vismara, F. Musumeci, M. Tornatore, and A. Pattavina. A comparative blocking analysis for time-driven-switched optical networks. In *Optical Network Design and Modeling (ONDM), 2011 15th International Conference on*, pages 1–6, Feb 2011.

[VRmCL09] Luis M. Vaquero, Luis Rodero-merino, Juan Caceres, and Maik Lindner. A break in the clouds: Towards a cloud definition. *ACM SIGCOMM Computer Communication Review*, 39:50–55, 2009.

[WFRGE+10] A. Willner, J. Ferrer Riera, J. Garcia-Espin, S. Figuerola, M. De Leenheer, and C. Develder. An analytical model of the service provisioning time within the harmony network service plane. In *GLOBECOM Workshops (GC Wkshps), 2010 IEEE*, pages 514–518, Dec 2010.

[WHL+14] Xiaohui Wei, Shoufeng Hu, Hongliang Li, Fan Yang, and Yue Jin. A survey on virtual network embedding in cloud computing centers. *The Open Automation and Control Systems Journal*, 6:414–425, 2014.

[WID+13] Anjing Wang, M. Iyer, R. Dutta, G.N. Rouskas, and I. Baldine. Network virtualization: Technologies, perspectives, and frontiers. *Lightwave Technology, Journal of*, 31(4):523–537, Feb 2013.

[WMA00] Xi Wang, Hiroyuki Morikawa, and Tomonori Aoyama. Deflection routing protocol for burst-switching wdm mesh networks. volume 4213, pages 242–252, 2000.

[XTL+14] G. Xilouris, E. Trouva, F. Lobillo, J.M. Soares, J. Carapinha, M.J. McGrath, G. Gardikis, P. Paglierani, E. Pallis, L. Zuccaro, Y. Rebahi, and A. Kourtis. T-nova: A marketplace for virtualized network functions. In *Networks and Communications (EuCNC), 2014 European Conference on*, pages 1–5, June 2014.

[YKS+10] Kok-Kiong Yap, Masayoshi Kobayashi, Rob Sherwood, Te-Yuan Huang, Michael Chan, Nikhil Handigol, and Nick McKeown. Openroads: Empowering research in mobile networks. *SIGCOMM Comput. Commun. Rev.*, 40(1):125–126, January 2010.

[YR11] R. Yrjo and D. Rushil. Cloud computing in mobile networks x2014; case mvno. In *Intelligence in Next Generation Networks (ICIN), 2011 15th International Conference on*, pages 253–258, Oct 2011.

[YYK+11] Yiannis Yiakoumis, Kok-Kiong Yap, Sachin Katti, Guru Parulkar, and Nick McKeown. Slicing home networks. In *Proceedings of the 2Nd ACM SIGCOMM Workshop on Home Networks*, HomeNets '11, pages 1–6, New York, NY, USA, 2011. ACM.

[YYW12] S.J.B. Yoo, Yawei Yin, and Ke Wen. Intra and inter datacenter networking: The role of optical packet switching and flexible bandwidth optical networking. In *Optical Network Design and Modeling (ONDM), 2012 16th International Conference on*, pages 1–6, April 2012.

[ZA06] Y. Zhu and M. Ammar. Algorithms for Assigning Substrate Network Resources to Virtual Network Components. In *INFOCOM 2006. 25th IEEE International Conference on Computer Communications. Proceedings*, pages 1–12, 2006.

[ZGLC03] Wei Zhuang, Yung Sze Gan, Kok Jeng Loh, and Kee Chaing Chua. Policy-based qos architecture in the ip multimedia subsystem of umts. *Network, IEEE*, 17(3):51 – 57, May 2003.

[ZRY+12] G. Zervas, B. Rofoee, Yan Yan, D. Simeonidou, G. Bernini, G. Carrozzo, and N. Ciulli. Control and transport of time shared optical networks (tson) in metro areas. In *Future Network Mobile Summit (FutureNetw), 2012*, pages 1–9, July 2012.

[ZTA+11] G.S. Zervas, J. Triay, N. Amaya, Y. Qin, C. Cervello-Pastor, and D. Simeonidou. Time shared optical network (tson): A novel metro architecture for flexible multi-granular services. In *Optical Communication (ECOC), 2011 37th European Conference and Exhibition on*, pages 1–3, Sept 2011.

Chaos is not a pit. Chaos is a ladder. Many who try to climb it fail, and never get to try again. The fall breaks them. And some are given a chance to climb, but refuse. They cling to the realm, or love, or the gods... illusions. Only the ladder is real. The climb is all there is. But they will never know this. Not until it is too late.